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Numerical Simulation Research and Use of The Steel Sheet Pile Supporting Structure in Vertical Excavation

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1. Introduction

Deep foundation pit construction is frequently limited by construction site, which is usually through vertical excavation instead of slope excavation. The steel sheet pile supporting structure is a special supporting method for vertical excavation widely applied in the base of high-rise buildings, underground railway, municipal engineering and hydraulic engineering, with better economic benefits and environment effects. The supporting structure is used to protect the foundation pit from sliding in the process of excavation of the foundation pit.

2. Survey of deep foundation pit bracing

In the 1930s, Terzaghi and other scholars studied excavation engineering in geotechnical engineering problems.
Early in the 20th century, steel plate piles were first developed in Europe. In 1903, in Japan, the steel plate was used for the first time in Mitsui library of retaining piles construction and found with special performance. Hence steel sheet pile were used in Japan for large and repair works after 1923 Great Kanto earthquake. In 1931, steel sheet pile was rapidly developed and produced in Japan, and then it also witnessed positive development, application and dissemination in Europe, South Korea, the United States and other countries.

3. Steel sheet pile supporting overview

3.1 Concepts of steel sheet pile supporting

The retaining part refers to the excavation, in order to ensure pit wall not to collapse, protect the security of underground structures and surrounding environment. Steel sheet pile supporting of foundation pit supporting structure is used in a type of steel sheet pile (general concurrently waterproof curtain) into the soil, set up necessary support or pull anchor, to resist earth pressure and water pressure, to keep the stability of strata, to maintain the balance of deep excavation and guarantee the smooth construction of.

3.2 Steel foundation pit supporting structure stability analysis

The purpose of the foundation pit supporting of excavation is to ensure stability in construction. Pit instability and failure mainly involves two kinds of problems.

For the first kind of problem of foundation pit stability, the supporting structure (including supports wall body, interior support, anchor, etc.) of the internal force (mainly moment) and displacement as the research object, is to determine the foundation pit supporting structure satisfy the intensity and rigidity requirement the stability problem. The second kind of foundation pit instability issues is mainly for supporting structure static equilibrium conditions, the main problems in the research of the supporting structure static condition are to satisfy the static equilibrium condition stability problem.

4. Numerical analysis of steel sheet pile foundation pit supporting structure stability

4.1 Introduction of finite element method in the application of foundation excavation stability analysis

There are two kinds of steel sheet pile supporting finite element analysis methods, elastic foundation beam method and plane strain finite element method. The elastic foundation beam method is the foundation pit medial soil as soil spring, regardless of the pile and soil contact. The property of slippage of interface between soil and steel sheet pile can be calculated in the process of constructing surface subsidence and the of foundation pit bottom uplift. Therefore, in the stability analysis of steel sheet pile supporting, we should choose the plane strain finite element analysis.

4.2 Steel sheet pile plane strain finite element analysis assumptions

Steel sheet pile supporting structure relies on steel sheet pile, soil anchor (or support) and soil under the common function of passive earth pressure, water pressure, earthquakes and other load. The finite element method to analyze steel sheet pile supporting structure, involves stem cell, beam element, soil unit, and contact elements and so on many kinds of element types. Considering the nonlinear problem, the situation is more complicated.

The length of the deep foundation pit bracing is usually long, plane strain finite element method along the length direction is often applied to take unit length calculation.

4.3 Nonlinear finite element μ

There will be through elastic non-linear model Duncan - Zhang (D - C) hyperbolic model to calculate the displacement and stress field of sliding body, and then through the form of table definition unit Mohr -Column criterion, and for each unit of the yield of state judge which satisfy Mohr -Column criterion the slope plastic differentiate code layout.

E_t the tangent modulus of elasticity

Soil tri-axial test, σ_3 remain unchanged, exert partial stress, point draw $(\sigma_1\text{-}\sigma_3)/\varepsilon_\alpha$ curve (see figure 1), Connor, etc, found that $(\sigma_1\text{-}\sigma_3)$ hyperbola can be used to fit these curves. For one σ_3, the relations of $(\sigma_1\text{-}\sigma_3)/\varepsilon_\alpha$ can be expressed as

$$\sigma_1 - \sigma_3 = \frac{\varepsilon_\alpha}{a + b\varepsilon_\alpha} \tag{1}$$

The Eq. (1) also takes the form

$$a + b\varepsilon_\alpha = \frac{\varepsilon_\alpha}{\sigma_1 - \sigma_3} \tag{2}$$

In which (σ_1-σ_3) refers to partial stress, ε_α axial strain, and a, b significance for test constants, the intercept and slope of curve in figure 2, are presented respectively as follows:

$$\begin{cases} a = \dfrac{1}{E_i} \\ b = \dfrac{1}{(\sigma_1 - \sigma_3)_u} \end{cases} \tag{3}$$

Here $(\sigma_1$-$\sigma_3)_u$ refers to the value of (σ_1-σ_3) when $\varepsilon_\alpha \to \infty$, ($\sigma_1$-$\sigma_3$) refers to progressive values (as shown in figure 3), E_i refers to the initial tangent modulus, obtains

$$E_i = kp_\alpha \left(\frac{\sigma_3}{p_\alpha} \right)^n \tag{4}$$

The P_a refers to atmospheric pressure, generally take 100kPa, *K* and *n* refers to trials have certain parameters, its significance see figure 1, available by the calculation

$$E_t = \frac{\partial(\sigma_1 - \sigma_3)}{\partial \varepsilon_\alpha} \tag{5}$$

Then ε_α=a(σ_1-σ_3)/[1-b(σ_1-σ_3)], Will ε_α generation into Eq.(5), obtains

$$E_t = \frac{1}{a}\left[1 - b(\sigma_1 - \sigma_3)\right]^2 = E_i\left[1 - R_f s\right]^2 \tag{6}$$

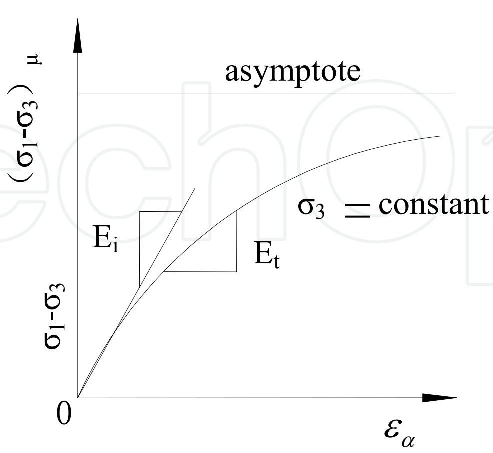

Fig. 1. The relation between (σ_1-σ_3) and ε_α

In which *S* refers to stress level, s=(σ_1-σ_3)/$(\sigma_1$-$\sigma_3)_f$, and R_f refers to the destruction of the stress ratio, R_f =$(\sigma_1$-$\sigma_3)_f$/$(\sigma_1$-$\sigma_3)_\mu$, less than 1, generally in between (0.75-1), and failing stress $(\sigma_1$-$\sigma_3)_f$ .With relevant consolidation pressure σ_3, as shown in figure 4, obtains

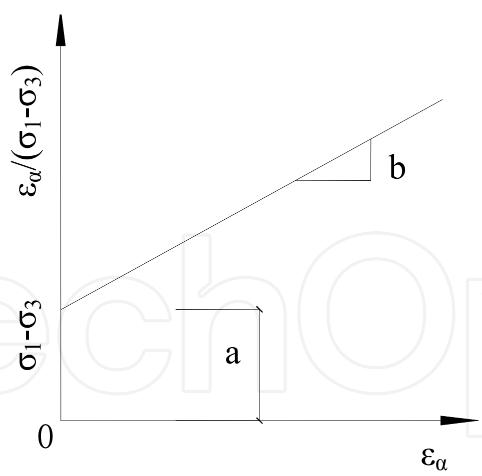

Fig. 2. The relation between $\varepsilon_\alpha/(\sigma_1\text{-}\sigma_3)$ and ε_α

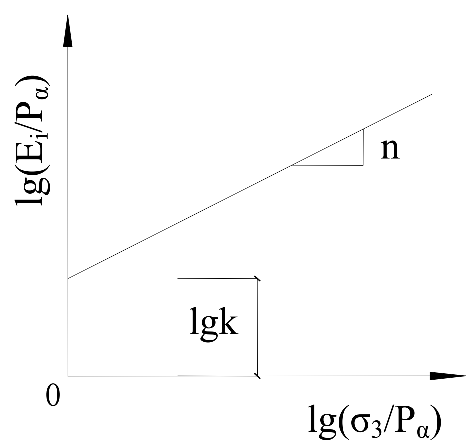

Fig. 3. The relation between $\lg(E_i/P_a)$ and $\lg(\sigma_3/P_a)$

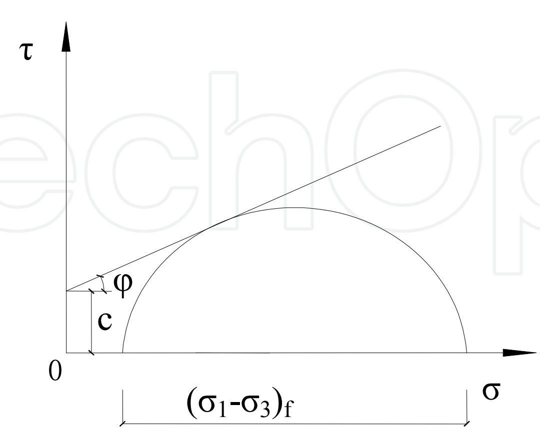

Fig. 4. Limit Mohr's circle

$$(\sigma_1 - \sigma_2)_f = \frac{2(\cos\varphi + \sigma_3 \sin\varphi)}{1 - \sin\varphi} \tag{7}$$

Substituting Eq.(6)into Eq.(7), it follows that

$$E_t = \left[1 - R_f \frac{(1-\sin\varphi)(\sigma_1 - \sigma_3)}{2(c\cos\varphi + \sigma_3 \sin\varphi)}\right]^2 k p_\alpha \left(\frac{\sigma_3}{p_\alpha}\right)^n \tag{8}$$

Here E_t refers to the tangent modulus of elasticity.
(2) Tangent of Poisson ratio
Kulhway and Dunkcan think conventional tri-axial test measured with the curvilinear relationship between ε_α and ε_γ may adopt hyperbola to fitting (see figure 5), and the curvilinear relationship between $-\varepsilon_\gamma/\varepsilon_\alpha$ and $-\varepsilon_\gamma$ for a straight line (see figure 6).Its interception is *f*, slope is *D*, then

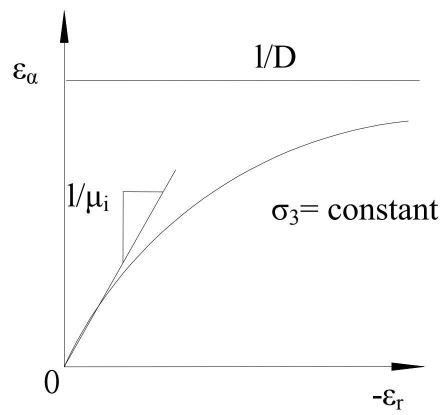

Fig. 5. The relation ε_α and $-\varepsilon_r$

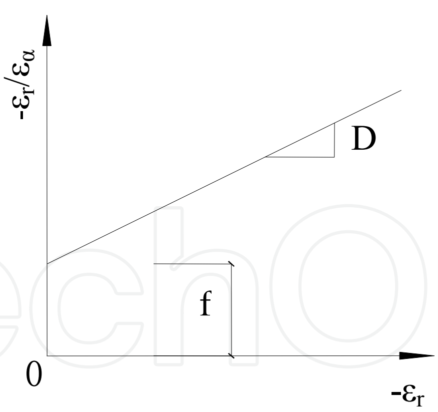

Fig. 6. The relation $-\varepsilon_r/\varepsilon_\alpha$ and $-\varepsilon_r$

$$\frac{-\varepsilon_r}{\varepsilon_\alpha} = f + (-\varepsilon_r) \tag{9}$$

Same is

$$-\varepsilon_r = \frac{f\varepsilon_\alpha}{1 - D\varepsilon_\alpha} \tag{10}$$

Because of the lateral pressure increment is zero, next Eq. is usable for Poisson ratio

$$\mu = \frac{-\Delta\varepsilon_r}{\Delta\varepsilon_\alpha} = \frac{\partial(-\varepsilon_r)}{(\varepsilon_\alpha)} \tag{11}$$

Substituting Eq. (10) into Eq. (11), and, will ε_α=a(σ_1-σ_3)/[1-b(σ_1-σ_3)] into Eq. (11), it follows that

$$\mu = \frac{f}{(1-A)^2} \tag{12}$$

In which A refers $A = \dfrac{D(\sigma_1 - \sigma_3)}{kp_\alpha\left(\dfrac{\sigma_3}{p_\alpha}\right)^n\left[1 - R_f\dfrac{(1-\sin\varphi)(\sigma_1-\sigma_3)}{2(c\cos\varphi + \sigma_3\sin\varphi)}\right]^2}$

By Eq.(10), when $-\varepsilon_r \to \infty$, ε_α is progressive values, then D the same of D=1/ε_α, when the reciprocal of the,

$$f = \left(\frac{-\varepsilon_r}{\varepsilon_\alpha}\right)_{\varepsilon \to 0} = \mu_i \tag{13}$$

In which μ_i refers to the initial tangent Poisson ratio.
For different σ_3 have different μ_i values, in half logarithmic coordinate system μ_i in the relationship with σ_3/P_a is a linear curve approximation (see figure 4-7), its intercept is G_γ, slope is F, therefore

$$\mu_i = G - F\lg\left(\frac{\sigma_3}{p_\alpha}\right) \tag{14}$$

So the tangent Poisson's ratio obtain by Eq. (15) solution

$$\mu_t = \frac{G - F\lg\left(\dfrac{\sigma_3}{p_\alpha}\right)}{(1-A)^2} \tag{15}$$

(3) Resilience modulus
Eq. (8) is elastic modulus in loading cases. For unloading cases, elastic modulus E_{ur} obtained by unloading test. In figure 8, OA is stress-strain curve of loading status, the slope is E_t, AB stress-strain curve of unloading status, the slope is E_{ur}. Obviously, $E_{ur} > E_t$. Duncan etc have supposed E_{ur} not changes with (σ_1-σ_3), only changes with σ_3, it is concluded that the relation curve of lg(E_{ur} / P_a)~lg(σ_3/P_a) is a straight line (see figure 9), its intercept is lgE_{ur}, slope is n.
Generally speaking, n basically consistent (elastic modulus as tangent modulus) in loading cases, while K_{ur}=(1.2~3.0)K. For close-grained sand and hard clays K_{ur}=1.2K, for loose sand and soft soil K_{ur}=3.0K, general soil K_{ur} value is between them. Resilience modulus can be calculated by next Eq.

$$E_{ur} = k_{ur}p_\alpha\lg\left(\frac{\sigma_3}{p_\alpha}\right)^n \tag{16}$$

The finite element calculation to give a standard K_{ur} under specific circumstance, this is actually a rough yield criterion. Can use such standard: when $(\sigma_1\text{-}\sigma_3) < (\sigma_1\text{-}\sigma_3)_0$, and $S < S_0$ use K_{ur}, otherwise use K_t. Here $(\sigma_1\text{-}\sigma_3)_0$ is the biggest variable stress in history has achieved. S_0 is the maximum stress historical levels history once reached.

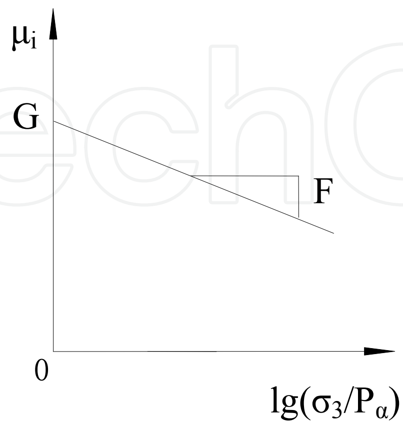

Fig. 7. μ_i～$\lg(\sigma_3/P_a)$ relation curve

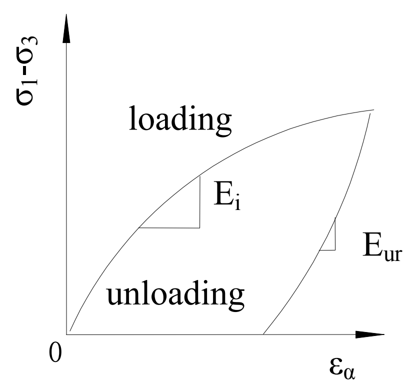

Fig. 8. Loading and unloading relation curve

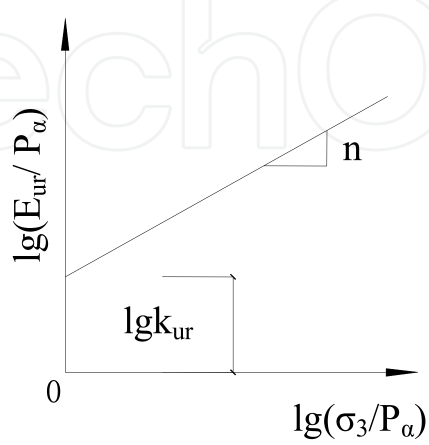

Fig. 9. $\lg(E_{ur}/P_a)$～$\lg(\sigma_3/P_a)$ relation curve

(4)Property indexes

Adopting Duncan - Zhang (D - C) elastic non-linear model of E-μ, the stress and strain of soil is of nonlinear properties. The concentrated reflection is summed up in Eq. (8) and (15) and (16), all parameters contains in Eq. are to be determined by conventional tri-axial test. Nonlinear plane strain finite element numerical analysis of steel sheet pile needs to determine that the physical and mechanical indexes such as γ, ϕ and c, and the elastic modulus index R_f, K and n, and Poisson's ratio index G, F and D, spring-back modulus index E_{ur} and m, all 11 parameters. Zhujun Gao, Zongze Yin put forward a optimal method of determining soil constitutive model parameters, put absolute error between the tri-axial test measurement of the stress-strain relationship curves and soil constitutive model of curve as objective function, to determine the soil constitutive model parameters.

2) Construction process simulation

In the normal soil excavation and backfilling calculation, it is often assumed that they will be instantaneously completed. But the construction process of excavation and backfilling could have influence on internal force and deformation produce of steel sheet pile structure should not be neglected, it is necessary to simulate the influence of foundation pit excavation and construction of backfill process. The excavation and backfilling is actually a hierarchical loading process, and backfill belongs to primary loading, the excavation is the unloading or an unloading reloading process. It has been proved in practice that incremental method can be used to simulate construction process. The key issue is that the proposed method can simulate the construction process adopted and load history, soil constitutive relationship should reflect the different stress path of soils, and the input parameters in calculation should be in accordance with the actual calculation, and the boundary conditions of should be as far as possible and reasonable.

Construction process simulation mainly includes a step-by-step excavation, exertion and removal of soil anchor and support, etc. The finite element equation the simulation of mechanical behavior of the different construction stage of can be written as

$$\{[K_0]+[\Delta K_i]\}\{\Delta\delta_i\}=\{\Delta F_{ir}\}+\{\Delta F_{in}\}(i=1,m) \tag{17}$$

In which m refers to total number of construction steps, K_0 the initial general strength degree matrix before excavation, ΔK_i incremental of stiffness of geotechnical body and the support structure in the construction process, the value is element stiffness of geotechnical body and supporting structure settled or dismantled, $\{\Delta F_{ir}\}$ refers released boundary incremental node force matrix of produced by excavation, determined in first excavation by geotechnical body self-weight, groundwater load, ground overloading, in followed excavation steps determined by the current stress state; $\{\Delta F_{in}\}$ refers the increased node force matrix in the construction process, $\{\Delta\delta_i\}$ refers the incremental displacement matrix of any construction stages. $\{\Delta\delta_i\}$ refers displacement, ε_i strain and stress σ_i matrix in ith step in the construction process

$$\{\delta_i\}=\sum_{k=1}^{i}\{\Delta\delta_i\},\ \{\varepsilon_i\}=\sum_{k=1}^{i}\{\Delta\varepsilon_i\},\ \{\sigma_i\}=\{\sigma_0\}+\sum_{k=1}^{i}\{\Delta\sigma_i\} \tag{18}$$

Generally speaking, load steps divided more, the analytical results is more close to reality. The more accurate the loading steps, the results are more close to reality. However, the fact that how many exact steps are divided is determined by the purpose of the relevant analysis. If the main purpose is to understand the deformation and stress of the foundation under the backfilling, the load steps can be fewer; If you need to understand the displacement and stress of backfilling itself, there can be more the load steps be added. Typical division into 10-12 may obtain satisfactory results. The typical process can be divided into 10- 12 steps to obtain satisfactory results. The amount of increment of the displacement in backfilling itself is very sensitive needs to be judged according to the measured data and the experience of the engineering representative.

There is another thing to be noted and is of vital importance is the unit application in the construction process simulation. All units generated in the pre-treatment, and then put the soil anchor or support unit killed, then put soil anchor or support unit killed after every excavation step, brought each unit of support or anchor activation after a layer each construction completed. Attention should be paid to reactivate or kill units in every step.

4.4 Unit types and strength degree matrix.

Steel sheet pile of plane strain finite element analysis will involves four units, which is described as follows: the soil unit, contact elements, beam element and line unit. The following is a simple introduction of various units unit strength degree matrix.

1. Beam element strength degree matrix

The plane beam element is shown in figure 4-10. Classic beam bending theory generally corresponding to the smaller depth-span beam, it meets normal sections the assumption. The strength degree matrix under local coordinate is

$$[K]^e = \begin{bmatrix} \frac{AE}{l} & & & & & \\ 0 & \frac{12EI}{l^3} & & & & \\ 0 & \frac{-6EI}{l^2} & \frac{4EI}{l} & & & \\ -\frac{AE}{l} & 0 & 0 & \frac{AE}{l} & & \\ 0 & \frac{12EI}{l^3} & \frac{6EI}{l^2} & 0 & \frac{12EI}{l^3} & \\ 0 & \frac{-6EI}{l^2} & \frac{2EI}{l} & 0 & \frac{6EI}{l^2} & \frac{4EI}{l} \end{bmatrix} \tag{19}$$

In which A refers to cross-sectional area of beam element, E elastic modulus of beam element materials, I moment of inertia of beam element cross-sectional inertia, and L refers to the beam element length.

Eq. (19) is the unit strength degree matrix of beam element in local coordinate, if θ is the angle between local coordinate system and integral coordinate system, the unit strength degree matrix of beam element under integral coordinate system is:

$$\left[\bar{K}\right]^e = [T]^T [K]^e [T] \tag{20}$$

In which $[K]^e$ is the unit strength degree matrix of beam element in the local coordinate, $\left[\bar{K}\right]^e$ is the unit strength degree matrix of beam element in the global coordinate system of units, $[T]$ is the coordinate transformation matrix of strength degree matrix. The calculation Eq. is

$$[T]=\begin{bmatrix} \cos\theta & \sin\theta & 0 & 0 & 0 & 0 \\ -\sin\theta & \cos\theta & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \cos\theta & \sin\theta & 0 \\ 0 & 0 & 0 & -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{21}$$

2. Line element strength degree matrix

Planar line element as shown in figure 4-11, the line element strength degree matrix in local coordinate is

$$[K]^e=\frac{EA}{l}\begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{22}$$

In which A refers to cross-sectional area of line element, E elastic modulus of line element materials of and L refers to unit length.

Line element unit strength degree matrix in local coordinate and integral coordinate system conversion also can process according (20), calculation is

$$[T]=\begin{bmatrix} \cos\theta & \sin\theta & 0 & 0 \\ -\sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & \cos\theta & \sin\theta \\ 0 & 0 & -\sin\theta & \cos\theta \end{bmatrix} \tag{23}$$

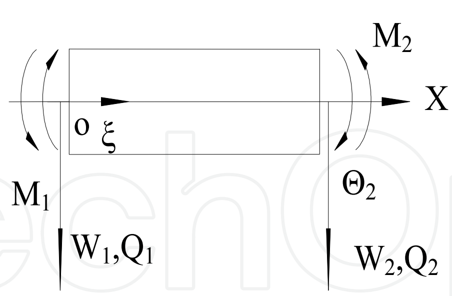

Fig. 10.

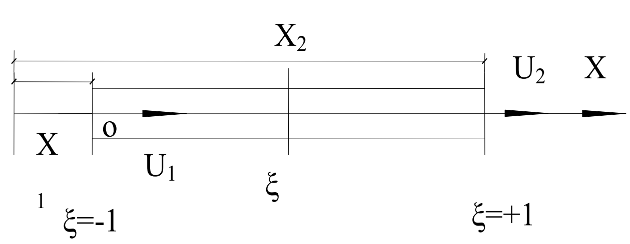

Fig. 11.

The support and soil anchor in three-d is discontinuous structures, how in the analysis of plane strain finite element simulation, which is an important issue of the steel sheet pile analysis. In situ and Clough study, once pointed out that exact a treatment is the board wall of strut (soil anchor) axial stiffness press unit length added. To support (soil anchors), it in the plane strain finite element analysis of axial stiffness by the support of the actual axial stiffness divided by supporting spacing.

3. Soil unit strength degree matrix

Soil element adopted the plane four nodes iso-parametric unit, the unit strength degree matrix calculation method is of the same as strength degree matrix of usual iso-parametric unit, just instead E and μ by E or E_{ur} and μ_t in the calculation, and the unit strength degree matrix of soil to be calculated by:

$$[K]^e = t\int_{-1}^{1}\int_{-1}^{1}[B]^T[D][B]|J|\,d\xi d\eta \tag{24}$$

In Eq. (24), $[B]=[B_1 \quad B_2 \quad B_3 \quad B_4]$ and $[B_i]=\begin{bmatrix} \frac{\partial N_i}{\partial x} & 0 \\ 0 & \frac{\partial N_i}{\partial y} \\ \frac{\partial N_i}{\partial y} & \frac{\partial N_i}{\partial x} \end{bmatrix}$;

$$[D]=\frac{E}{1-\mu^2}\begin{bmatrix} 1 & \mu & 0 \\ \mu & 0 & 0 \\ 0 & 0 & \frac{1-\mu}{2} \end{bmatrix}, \ . \ |J|=\begin{vmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial y}{\partial \xi} \\ \frac{\partial x}{\partial \eta} & \frac{\partial y}{\partial \eta} \end{vmatrix}$$

4. Contact surface elements strength degree matrix

In contact surface of steel sheet pile and soil, there is a great difference in material property. In some conditions, slippage or craze could be generated possibly on the contact interface, so it is suggested to set contact surface elements to simulate the interaction between steel sheet pile and soil.

Goodman and others propose the joints units, commonly used in contact elements. This unit is no thickness four nodes unit, as shown in figure 12, the idea is to have countless normal and tangential tiny spring associated between two contact interfaces, and stress and relative displacement relations is described as:

$$\begin{Bmatrix} \sigma \\ \tau \end{Bmatrix} = \begin{bmatrix} k_n & 0 \\ 0 & k_s \end{bmatrix} \begin{Bmatrix} w_s \\ w_n \end{Bmatrix} \tag{25}$$

In which w_s refers to tangential displacement, and w_n normal relative displacement, K_s tangential spring coefficient, and K_n normal spring coefficient.The unit strength degree matrix is available under local coordinate.

$$[k]=\frac{L}{6}\begin{bmatrix} 2k_s & & & & & & & \\ 0 & 2k_n & & & & & & \\ k_s & 0 & 2k_s & & & & & \\ 0 & k_n & 0 & 2k_n & & & & \\ -k_s & 0 & -2k_s & 0 & 2k_s & & & \\ 0 & -k_n & 0 & -2k_n & 0 & 2k_n & & \\ -2k_s & 0 & -k_s & 0 & k_s & 0 & 2k_s & \\ 0 & -2k_n & 0 & -k_n & 0 & k_n & 0 & 2k_n \end{bmatrix} \tag{26}$$

To determine K_s by direct shear tests, to determine point remit $\tau \sim w_s$ relation curves by hyperbola assumptions:

$$k_s=\left(1-\frac{R_f \tau}{\sigma_n tg\delta}\right)^2 k_1 \gamma_w \left(\frac{\sigma_n}{p_\alpha}\right)^n \tag{27}$$

In which K_i, n and R_f, refers to as the test parameters, δ refers to the friction angle between soil and structural materials, δ refers to water volume weight. Elasticity coefficient is relevant with stress state, in response contact surface pulled open, give K_n a small value, or take a big value.

By coordinate transformation, the unit strength degree matrix $[K]$ is obtianed in the global coordinate system

$$[K]=[Q]^{-1}[k][Q] \tag{28}$$

$[Q]$ is coordinate transformation matrix

$$[Q]=\begin{bmatrix} \alpha & & & \\ & \alpha & & \\ & & \alpha & \\ & & & \alpha \end{bmatrix},\ [\alpha]=\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$$

5 The numerical analysis of engineering examples

5.1 Project profile

The engineering site stratum structure and the causes of stratum structure are very simple, and the variation in thickness of the stratum is low. The average ground elevation is 5.50m, and the depth of the foundation pit is 10.00m. The area of engineering site is 3745 square meters, and the area of supporting structures is 4180 Square meters.

5.2 Geological conditions of the site

There are nine geological stratums in the depth range of 35m according to field exploration and comprehensive analysis of laboratory test, by the litho logy of the geological stratums are composed mainly of plain fill, silt, silt-clay and mealy sand.

5.3 Design decision of the supporting structure

The standard section of foundation pit supporting structure is shown in Figure 12. The model of steel sheet pile is H formed steel, whose width is 486mm, and the depth of section is 420mm, and elastic section modulus is 3.12×106mm3. The length of pile is 16.00m. The elevation of pile cap is +5.50m, and toe is -10.50m. The location's elevations of two layers of pre-stressed strands anchor are +1.50 m and -1.50m, and the angle between soil anchor and horizontal plane is 15. The first layer of soil anchor is made by 3 bunches of steel strands and each bunch is consisted of 7 lines. The freedom length is 5.00m, and the designed length of anchoring section is 10.00m; The second layer of soil anchor's component is similar to the first one. The freedom length is 5.00m, and the designed length of anchoring section is 10.00m. The length between soil anchors is 2.50m. Because it is very difficult to control the location of steel sheet pile exactly and steel sheet piles can not bond join each other very well, it needs to set a row of DJM piles acting as curtain for cutting off water, for the steel sheet pile has the effect of cutting off water. The length of DJM pile is 13.00m, diameter is 0.50m, cement-mixed ratio is 15%, and the length between piles is 0.40m.

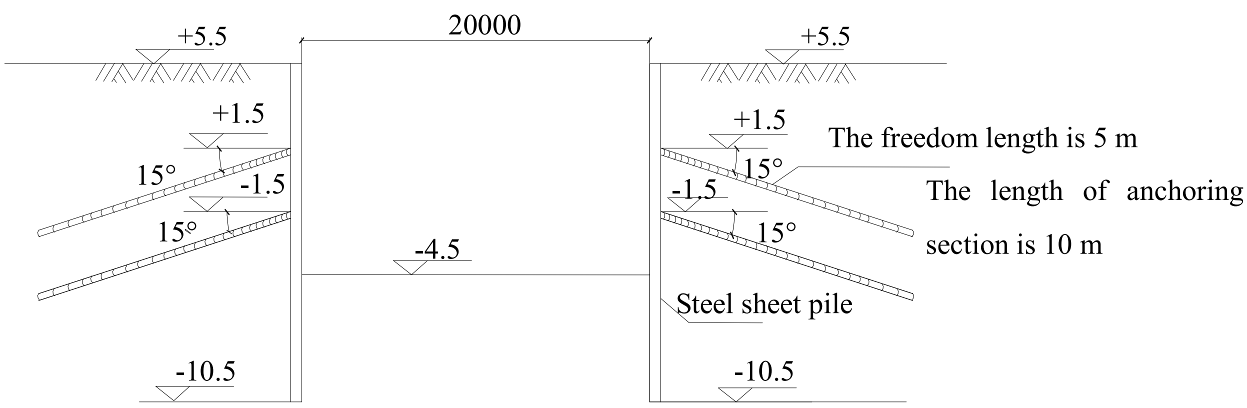

Fig. 12. Foundation pit support sectional drawing

5.4 Decision of computational model

It takes half of model to carry out analogue computation, because the structure is symmetrical. The width of that the foundation pit can effect is 3-4 times as the width of excavation and the influence depth which is 2-4 times as [a, b] according to the project experience. In this project, the width of excavation is 20.00m, the depth of excavation is 10.00m, the influence width is 30.00m, and the influence depth is 35.00m.

The finite element analysis method of steel sheet pile is applied to simulate construction of foundation pit supporting structure. It uses the 2—dimensional, 4—node iso-parametric element and D-C constitutive model to simulate soil mass. It uses 2—dimensional 2—node beam element to simulate steel sheet pile. It uses bar element to simulate the soil anchor, supporting structure and bottom brace. It takes equivalent elastic modulus as elastic modulus. It takes calculation under ten-stage loading, and there are ten increment steps in each stage (load sub-step). Some special construction stages of the first and the second layer of soil anchors are applied, including pre-construction, after construction and construction completion, to research horizontal displacement and settlement of steel plate pile, moment of steel sheet pile and axial force of soil anchor.

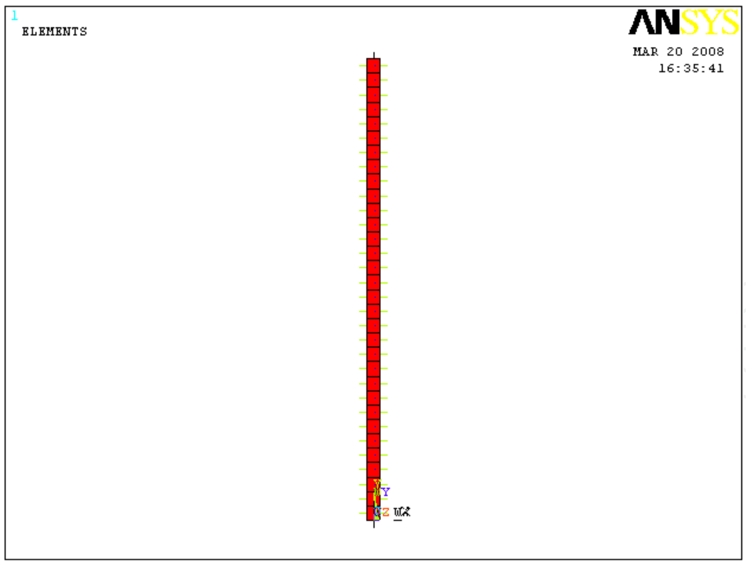

Fig. 13. Setting contact surface element between steel sheet pile and soil

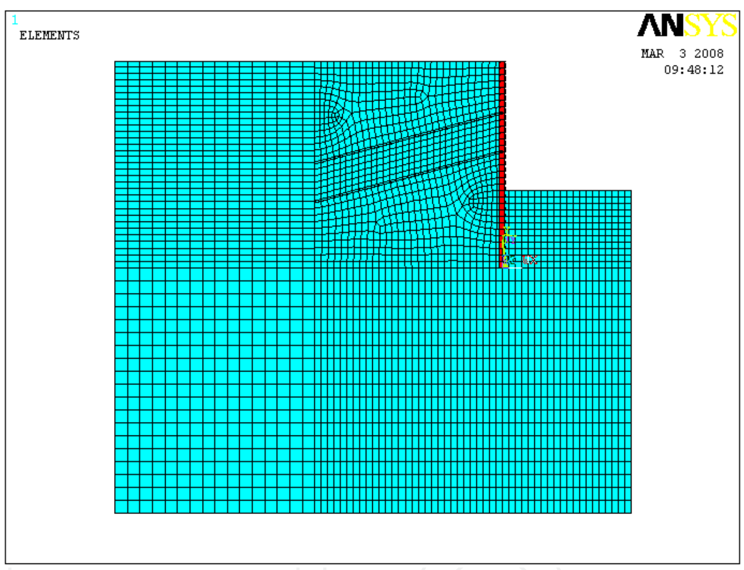

Fig. 14. Finite element analysis mesh of steel sheet pile foundation pit support schematic diagram

5.5 Results and analysis (horizontal displacement and settlement)

1. Horizontal displacement

From the Figure 15, the horizontal displacement curve calculated with the finite element method is similar to the measured displacement curve by and large. While the calculated displacement value is bigger than measured displacement value, the calculated maximum displacement value is 0.041m, and the depth is about 8.00m. The measured displacement value is 0.035m, and the depth is about 8.00m too.

2. Settlement

The settlement curves of ground after steel sheet pile in the different stages are shown in Figure16. The settlement will increase with the increase of excavation depth, and the location in which the maximum settlement happened is as long as excavation depth away from piles. Pre-stress will increase and maximum settlement points will be far away from pit wall after we set the first row of anchors. With the excavation of the foundation pit, the settlement will go on increasing, and the maximum settlement points are still away from the pit wall owing to the effect of the last layer of anchors. After setting the second row of anchors, there are few effects on the settlement. The reason may be that the anchoring section of the second row of anchors is too long. With the increase of excavation depth, ground settlement will increase again.

3. Uplift of foundation pit

From comprehensive analysis of these three excavation stages, the vertical settlement values of foundation pit are 6.2cm, 10.1cm and 12.3cm, and the settlement value is in the range of safety. The measured values are 5.5cm, 11.1cm and 13.8cm.

5.6 Internal force

1. Moment of steel sheet pile

The moment curves of steel sheet pile in the different stages are shown in Figure 17. The moment of pile shaft above the first layer of soil anchors is caused by active earth pressure. The moment remains about the same in the course of excavation, because the anchor can be seen as pivot and the part above pivot can be seen as cantilever structure. The cantilever structure is almost not changed in the course of excavation, because the steel sheet pile has no negative displacement, and this part has always been bearing consistent active earth pressure. After the first anchorage starts being constructed and exerts pre-stress, negative moment decreases and positive moment increases, but the absolute value of moment decreases, so soil anchor not only controls the horizontal displacement of the steel sheet pile well, but also improves its condition of forces. After the second excavation, excavation face goes down, earth pressure and moment increase. After the second anchorage starts construction and exerts pre-stress, negative moment increases, positive moment decreases and the maximum absolute value of moment decreases. So the second row of soil anchors control the horizontal displacement of the steel sheet pile and improve the condition of

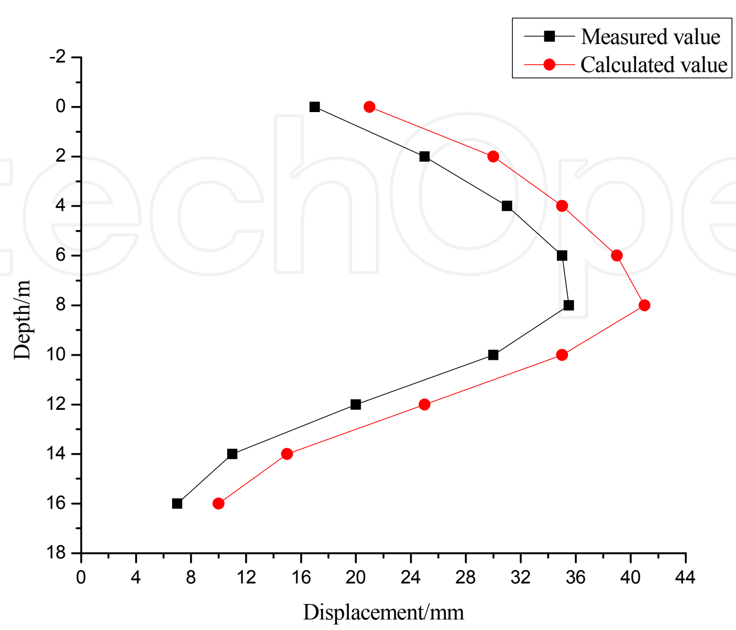

Fig. 15. Final calculated and measured values of horizontal displacement curve graph

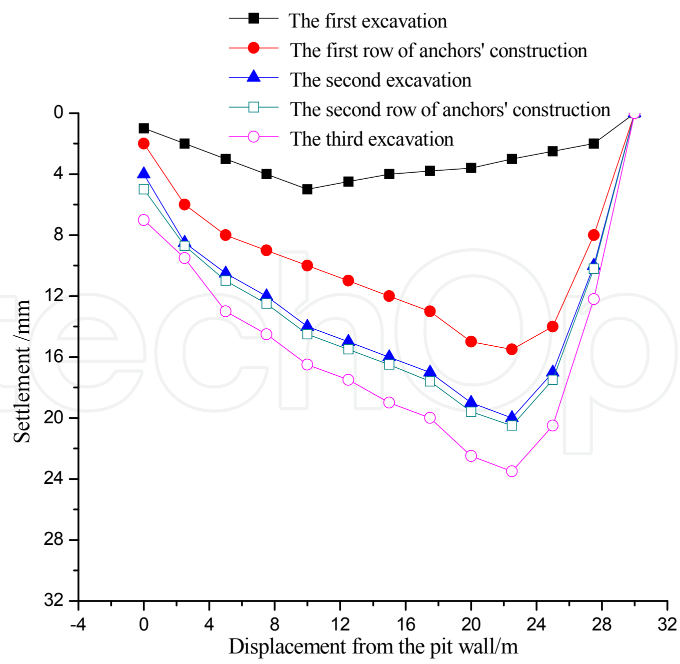

Fig. 16. Ground settlement behind pile curve graph

forces too. The maximum moment of the steel sheet pile happens in the stage of the last sub-step, and the maximum bending stress satisfies with the request of strength.

2. Anchor's shaft force

From chart 18, the shaft force of every layer has different levels of increase with the carrying out of excavation. After the consummation of the second excavation, the first layer of anchorage's shaft force has greatly increased. After the second anchorage starts being constructed and exerts pre-stress, the upper anchor will emerge stress relaxation, and the shaft force has a little decrease. After the third excavation, the shaft force of two layers of anchorage will bear new load, so it increases. The axial force of the first layer of anchors which is calculated by FEM increases from 151.21 KN to 249.63 KN with the process of loading. It is similar to the measured data. And because the shaft force of the second goes down to 180.34KN and then increases to 238.95KN, it is similar to the measured data 238.15KN. Looking at the second layer of anchors, the shaft force increases from 149.25KN to 264.87KN, and it's also similar to the measured data 263.22KN.

6. Conclusion

6.1 Conclusion

1. This paper mainly studies on the models and mechanism of steel sheet pile, and proposes two kinds of instability problems about the steel sheet pile: First, the supporting structure has not enough strength or stiffness to support the load and there are several destruction forms including support buckling, pull-anchor damage, excessive deformation of the supporting structure and bending failure. The second problem is the soil instability of the foundation pit.

   The forms of instability include sliding of foundation pit, subversion of the supporting structure, kick damage of the supporting structure, uplift instability of the foundation pit soil, leakage instability of foundation pit (piping or drifting sand) and heavy-piping instability of the foundation pit soil. The mechanics method is applied to obtain the

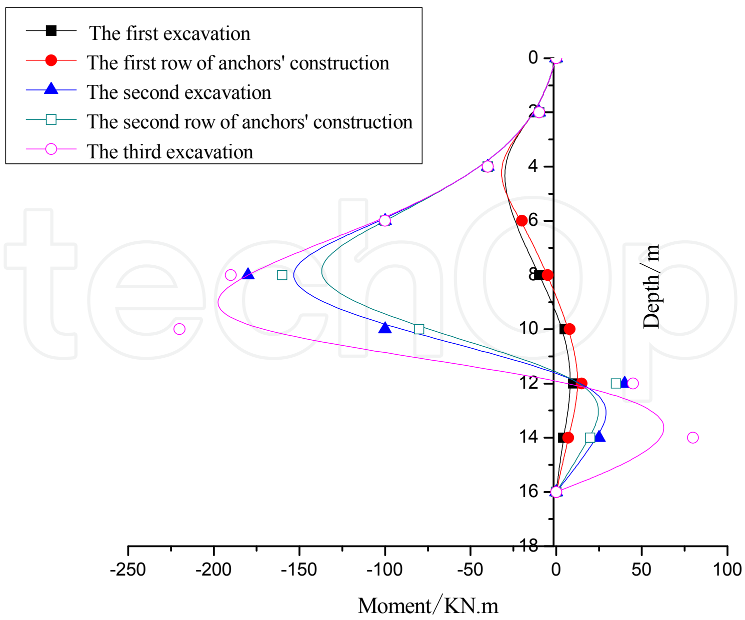

Fig. 17. Moment of steel sheet pile curve graph

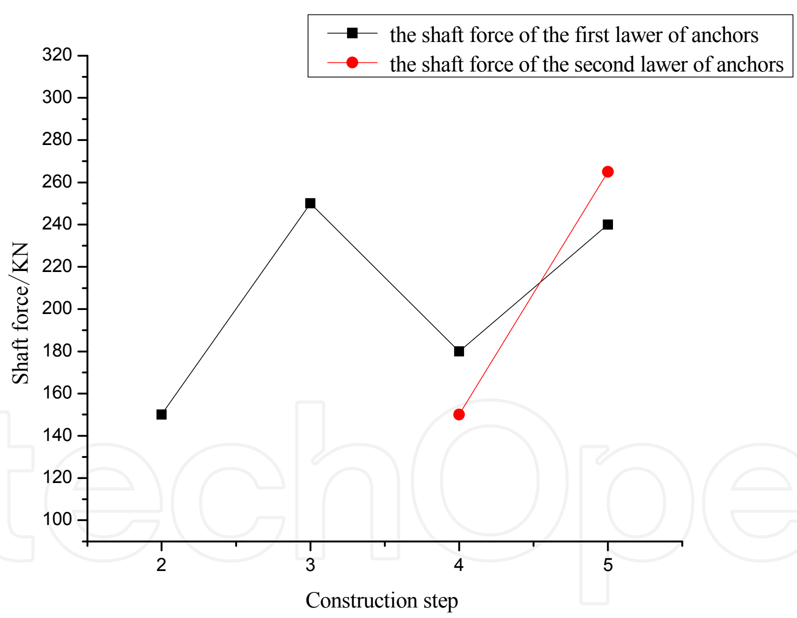

Fig. 18. Axial force of soil anchor curve

code formula from a reasonable discussion and systematical analysis. In the first instability problem, it uses the equivalent beam method and "m" method of elastic foundation beam methods to obtain the conclusion that the finite element method is a more ideal stability analysis method which we can use to deal with the strength problems and deformation problems, because the equivalent beam method does not involve the structure's deformation and "m" method does not involve the strength problems of soil.

2. In the second type of instability problems, according to the different steel sheet pile supporting basic form, and put forward different form steel sheet pile foundation pit supporting overall sliding stability analysis superposition methods, namely: Steel sheet pile supporting the stability analysis method, the influence of water that its safety coefficient calculation Eq. is:

$$K_S = \frac{\sum_{i=1}^{n}(W_i \cos\theta_i - \mu_i L_i)\, tg\varphi_i' + C_i' L_i}{\sum_{i=1}^{n} W_i \sin\theta_i} \tag{29}$$

3. Supported steel sheet pile retaining stability analysis method. Its safety coefficient calculation Eq. is:

$$K_S = \frac{\sum_{i=1}^{n}[(W_i \cos\theta_i + Q_H \alpha_k \sin\theta_i)\, tg\varphi_i + C_i L_i]}{\sum_{i=1}^{n} W_i \sin\theta_i - Q_H \alpha_k \cos\theta_i} \tag{30}$$

4. Have anchor steel sheet pile retaining stability analysis method. Its safety coefficient calculation Eq. is:

$$K_S = \frac{\sum_{i=1}^{n}(W_i \cos\theta_i tg\varphi_i + C_i L_i) + \sum_{j=1}^{m} T_j (\sin\beta_j tg\varphi_j + \cos\beta_j) / S_h}{\sum_{i=1}^{n} W_i \sin\theta_i} \tag{31}$$

The two types of instability problems combine, focus on the soil and steel sheet pile between interface slippage characteristics of plane strain finite element method and the methods of realization in software, in f foundation excavation engineering examples, this method sheet pile supporting stability analysis of practicality.

6.2 Prospects

In this paper, the stability of the steel sheet pile supporting has just made some preliminary studies in numerical simulation analysis, due to the limited conditions of the foundation pit supporting soil constitutive model parameters, the Duncan a (D - C) soil constitutive model parameters are given access to relevant information, resulting in the numerical calculation results there are certain differences, due to the complexity of soil properties of materials, the parameter value is often very difficult to grasp, should pass tests, and to determine the soil constitutive model parameters are optimized in the analysis; and this paper a symmetric model is used to take the half, this analogy is not quite reasonably, because even before the soil level of excavation isotropic, but often undergone asymmetry of foundation pit excavation, it will cause the whole system of foundation pit of stress and deformation fields of asymmetry. Therefore, there is still large room for further improvement in using numerical simulation to analyze the stability of steel sheet pile supporting.

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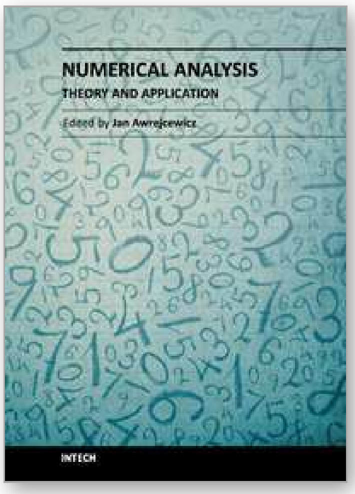

Numerical Analysis - Theory and Application

Edited by Prof. Jan Awrejcewicz

ISBN 978-953-307-389-7
Hard cover, 626 pages
Publisher InTech
Published online 09, September, 2011
Published in print edition September, 2011

Numerical Analysis â€“ Theory and Application is an edited book divided into two parts: Part I devoted to Theory, and Part II dealing with Application. The presented book is focused on introducing theoretical approaches of numerical analysis as well as applications of various numerical methods to either study or solving numerous theoretical and engineering problems. Since a large number of pure theoretical research is proposed as well as a large amount of applications oriented numerical simulation results are given, the book can be useful for both theoretical and applied research aimed on numerical simulations. In addition, in many cases the presented approaches can be applied directly either by theoreticians or engineers.