Numerical Modeling of Supporting Structure Performance during Excavation

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ABSTRACT

A numerical analysis procedure based on the finite element method (FEM) is proposed to simulate the staged construction process, in parallel with the excavation layer by layer. The key techniques in establishing the method, including selection of simulated archetype, simulating methods, and processed design, were discussed through proposing an integrated method in estimating calculating range of the model and an alternating method in evaluating the prestress in struts, introducing the Hardening-Soil (H-S) model, respectively designing the basic construction process and scheme of strut prestressing, both considering the changes of geo-structure and construction load. The results of the numerical analysis reflect the gradual variation in the soil-structure interaction and construction load and their inter-influence.

KEYWORDS: foundation pit; excavation; FEM; H-S model; strut prestressing.

INTRODUCTION

The support engineering of *soft-deep excavation* (i.e. deep excavation in soft soil) includes retaining wall construction, sealing around deep foundation pit, in layers of soil excavation, layer-by-layer support, operation zone precipitation, and other areas of concern. The danger of excavation is always a “hotspot” [1−7]. The results show that soil excavation and unloading will aggravate soil pressure difference inside and outside retaining wall, and then change the supporting structure, such as the internal forces and deformation behavior. Further, we can see that as the excavation progresses, on the one hand earth pressure difference increases on both sides of retaining wall, on the other hand the increasing depth of retaining wall makes the capability of resisting lateral deformation decrease, which greatly increases the risk of pit collapse. In engineering practice, these problems are not completely solved by the measures that retaining wall increased stiffness and embedding depth of support pre-axial force on. Pit deepened caused both supporting failure and lead a series of major project accidents [8]. And it is also frequent that support programs designed conservative cause recessive waste in engineering examples. These cases indicate that the understanding and awareness is not enough to the mechanism of interaction of soil structure on the excavation process of undisturbed soil, especially to the mechanism of the existing support structure because of the pit deepened . So it is academic value and significant to research the subject project. And it is urgent task to study depth system in Soil mechanics and geotechnical engineering.

RAISED ISSUES

In the process of soft-deep excavation deepened, the changes of the work character of support structure are impacted by the soil structure, the gradual change of load, geotextile material and media diversity. So it is difficult to being based on accurate, comprehensive analysis. The author thinks that it relates mainly to the following Several issues.

(1) The change of Geotechnical structure

Pit soil dredged with precipitation changed the displacement boundary conditions and seepage boundary conditions. And the length ratio of cantilever and the fix-end of retaining wall and Support systems were also changed. This processes orderly changes in the soil structure.

(2) The changes of Construction load and structural response geotextile

These construction loads, such as Unloading of soil excavation, the percolation of precipitation, the erecting of support, the pre-axial force application, imposed to the geotextile structure changed in accordance with the step-by-step construction sequence and triggered stress redistribution. In addition, on the act of Unloading - reloading, soil shear wall and the arch effect of soil, the deformation modulus of soil in the pit will change and affect its construction load Response.

(3) The sensitivity parameters of Supporting Structure Design and Construction

At the same project of precipitation in excavation, different supporting structure has different response degrees. Some construction parameters, such as retaining wall stiffness, support stiffness, layout patterns, and support pre-stress etc, affect the precipitation in excavation. The sensitivity of parameters will be further researched.

According to the complex and the levity of geotechnical structural stress and strain in the course of excavation, the author proposes a numerical analysis model to dynamic simulate the effect on support structure because of pit deepened. Another thesis will explain the use of this model and the analysis results. These articles do not attempt to conduct a comprehensive discussion of these issues on a particular issue or give the final answer, and only put forward some doubt on the basis of existing work, even only some of the views, and expect to cause further study and discussion.

NUMERICAL MODELING

Basic conditions

The soft-deep excavation work was principally distributed in underground garage, commercial development, subway stations, underground mall and the soft-based region of coastal and riverside areas, the Great Lakes. These gradually showed the characteristics of deep, big and bear [9]. Due to environmental effects and the effect of supporting, the underground continuous wall and multi-channel combined support is the main support program in the control of soft ground deformation. Among them, the form of most deep excavation is a long strip, and the material of support is steel and it acts on the retaining wall directly. General construction pit have irregular shape and support size is larger. And support system is built on pit-type and long-distance support often establish column each 10 to 15m.

In the choice of modeling prototype, because the stress and strain of the deep pit mainly are concentrated in the larger central region and the bottom of retaining wall, but the supporting Selection is inclined to light weight, convenient and rapid entry and it is not suitable for long-distance support for a separate steel support ,the author selects a central region of a long strip of soft-deep excavation for 2-D finite element analysis, considering the prototype representation and integrated simulation feasibility. The underground continuous wall and multi-channel steel support was selected as the type of support and sealing measures was set up, which could simulate work conditions following construction method with space-time effect [10], such as layered, sections, symmetry, balance excavation, the digging and shoring, applying prestress. In addition, thanks to the characteristics of large area and deep excavation of the prototype pit, multi-level precipitation method usually was selected. The model applying for irregular Pit Support System will be discussed successively.

Computational analysis methods

The calculation region and boundary conditions

The Features of the pit is depth of 14m, half-width of 10m. Underground continuous wall-fixed is depth of 7m.The horizontal interval of steel support is 5m.The height in vertical direction is lower 1m, 4m, 7m, 10m than the ground and an average vertical interval is 3m. The upper of strata is artificial filled soil within 1m and the lower is deep soft soil and the surface is level. Groundwater is mostly of diving type and initial water table is 2m deep.

Assuming that wall is long enough to support structure and the surrounding conditions are identical, the prototype can be viewed as axisymmetric plane strain problem. The Features of the calculated geometric model in this paper is width of 50m and height of 35m. In the course of selecting the calculation region, they are also considered that the range of influence of seepage excavation and retaining wall depth, apart from the factor of considering lowering effect of the boundary error,

The range of influence about the seepage, the model does not accurately simulate the effect of precipitation on soil strength values, the amount of deformation, but considers whether the seepage caused by precipitation. More detailed analysis about seepage of foundation pit please refers to [11, 12], the approach taken here is as follows: supposing that the pit is a big pit wells, hydraulic gradient of soft soil is roughly 1:4, considering the effect of waterproof measures at dorsal wall and the discount coefficient is of 0.5, thus the range of influence about the seepage can be calculated in accordance with the depth. Building foundation pit regulation[13] demands that the final precipitation depth is not less than 0.5m from the bottom of the pit, but Shanghai Metro Pit regulation [14] requires that is not less than 1.0m.To the model, the aquifer is the soft soil, so the final precipitation depth is of 1 m from the bottom and the influence radius of seepage is of 26 m. The calculation results according to the calculation method recommended by regulation [13] is similar to upper value. Based on the discounted value of the hydraulic gradient, we can identify different the range of influence about the seepage according to different precipitation depth.

The range of influence about the excavation can be broadly in 2H (deepened) through a trial calculation and the regulation [13, 14] requires the range of monitoring about ground settlement is not less than 2H, so it is set to be 28m; The boundary at the bottom of pit general is set to be 2-4D (the built-in depth) according to the embedded depth of retaining wall.

In sum, the dorsal boundary of retaining wall is of 40m away from the outer wall and it is decided to a vertical sliding boundary; The boundary at the bottom of pit is of 35m and it is determined to a fixed restrained boundary; The inner boundary of retaining wall is of 10m away from the inner of retaining wall, and surface is set to be free boundary. Diagram about geometric boundary conditions and support structure are showed in Figure 1.

Geotextile material model and parameters

The geotextile materials about the model included artificial fill, soft soil, underground continuous wall and steel support. About the selection of material model, the author considered the material characteristics and behavior of the mutual influence between materials. Model parameters were decided on the basis of the parameter values come with in software and experience.

As mentioned above, the construction load and the secondary effects had the influence on deformation modulus of soil. On the choice of material model, the author considered the thickness of artificial fill has less effect, so selected the Mohr-Coulomb (MC) model; But deep soft soil had obvious effect, so the author selected Hardening-Soil (H-S) model to simulate soil which adopts plastic theory considering nonlinear stress-strain relationship and hyperbolic stress - strain curve on the basis of MC model. More detailed description about HS model please refers to [15]. In the process of Precipitation, soil strength increases could not be ignored [16]. The author regarded those as a safety margin. About material model and parameters of artificial fill and soft soil are shown in Table 1 and Table 2.

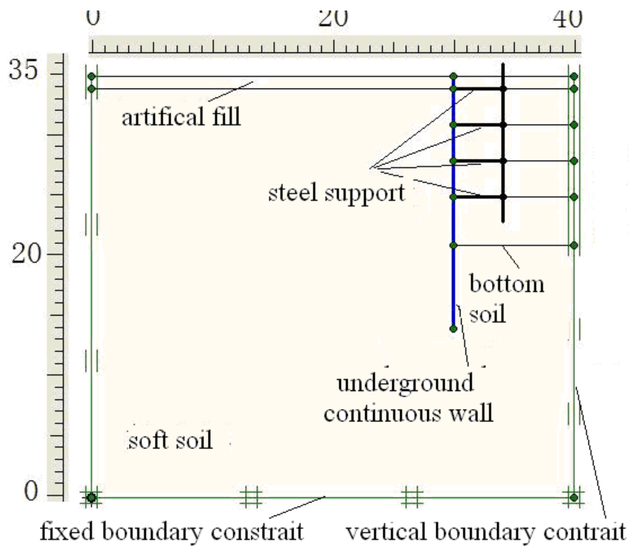

Figure 1: Sketch map of geometric boundary condition and supporting structures

Presumed underground continuous wall and steel support were the range of linear elastic in the process of controlling the horizontal displacement of the wall, thus underground continuous wall were considered as plate element. Owing to dislocation may happen between the wall and the soil, the interface element was introduced to simulate. The interface st-rength was discounted at two section in accordance with the soil strength (refer to table 1 and table 2) In order to meet the needs of deformation of plate element fully, the contact surface was expanded at the next section plate element. Contact element intensity at the expanded region was soil strength. However, the contact surface impervious, but the actual expanded region was pervious. When seepage was analyzed, the contact element must be closured. Steel support was considered as ingot steel anchor rod and its axial stiffness was of 2×10^6 kN. Material parameters for underground continuous wall were shown in Table 3.

Initial conditions

The initial conditions were decided when the first shoring was finished according to the demands of support structure, then simulated underground continuous wall construction, excavation to the elevation of the first shoring, the construction to the first shoring , the initial precipitation processes for pit. The resultant stress field simulated is regarded as the initial stress field.

The elevation of the first shoring is regarded as the standard for Initial excavation depth, which accord with the demands for the time-space effect and prohibiting overbreak. the Depth of the initial precipitation is determined mainly by the actual capacity of precipitation and water level at the work area. To the vacuum well point dewatering method, the regulation [13] proposed a multi-deep pit precipitation should be adopted and single-stage precipitation does not exceed 6m, and the precipitation should be less than 1m below at the face. In addition, when the precipitation depth is larger, the construction has difficulty and long construction period, so the initial precipitation depth is of 3m.

Design Conditions

Construction method of space-time can reduce the influence of time [17], this model assumes that the construction load is imposed instantaneously. Soft-deep excavation is a multi-stage process of follow-up; this model uses the step-by-step construction method for simulation. Initial conditions, the workload of excavation includes 13m excavation, three support erected, and 10m precipitation. In addition, that also includes the initial support pre-stress imposed and imposed once again. Based on the construction method of supporting at first and excavating behind and excavating along with supporting, the simulation of four excavations and four precipitations is application. The excavation depth at the first three is of 3 m and at the last time is of 4m; precipitation depth is as same as the excavation depth.

Table 1: Parameter values for artificial fill

Saturation density kN/m^3	Non-saturation density kN/m^3	horizontal permeability m/day	Vertical permeability m/day	elastic modulus (MPa)
16.0	20.0	1.0	1.0	8.0
Poisson's ratio	Cohesive force kPa	Friction angle °	Interface reduction coefficient	
0.2	1.0	30.0	0.65	

Table 2: Parameter values for soft soil

Conventional parameters	Saturation density kN/m3	Non-saturation density kN/m^3	horizontal permeability m/day	Vertical permeability m/day
	16.0	18.0	0.001	0.001
	Poisson's ratio	Cohesive force kPa	Friction angle °	Interface reduction coefficient
	0.2	5.0	25.0	0.5
Characteristic parameters	Consolidation drainage triaxial test secant modulus MPa			Tangent compression modulus MPa
	20.0			20.0
	Unloading and loading modulus MPa			Modulus Stress intersection exponential
	60.0			1.0

Table 3: Parameter values for underground continuous wall

Axial stiffness kN/m	Flexural rigidity, kN/m	Equivalent thickness, m	Bulk Density, kN/m/m	Poisson's ratio
7.5×10^6	1.0×10^6	1.265	10	0

Through the complete simulation to pit deepened, the basic conditions were established about the model (Figure 2) The status was composed of seven construction procedure, the range of influence about every seepage in the process of precipitation could be calculated by the method introduced. The basic conditions include working procedure cycle which is similar to construction parameters designed at the first three and construction procedure groups with danger at the last, which facilitate the comparison for the outcome between the recycling of construction procedure and different design parameters.

The effect of pre-stress imposed about multi-channel support systems is related to imposing size, location, the time, imposing once again and other complex factors, so the determination of optimization schedule should be further research. As the first shoring is close to the ground, and when it is erected along with pre-stress imposed, which could lead to soil-compacting at the top of the retaining wall and uplift around the pit. It is foreseeable. If pre-stress is not imposed, the first shoring has less control capability of deformation and the lateral displacement at the top of the retaining wall will be develop rapidly. In addition, the face about the simulation to the last excavation (corresponding to the status of basic processes 7) is deep, and the excavation height are larger than other construction produce, and the danger level will be greater than those of other excavation work. In sum, this model uses the support of pre-stress increased to optimize the conditions and its design is: to the first shoring, initial pre-stress were not imposed, and to the other support, pre-stress were imposed in the correct processes 6. For the needs of analysis, there also set up two conditions for reference. The name and descriptions of three conditions are shown in table 4.

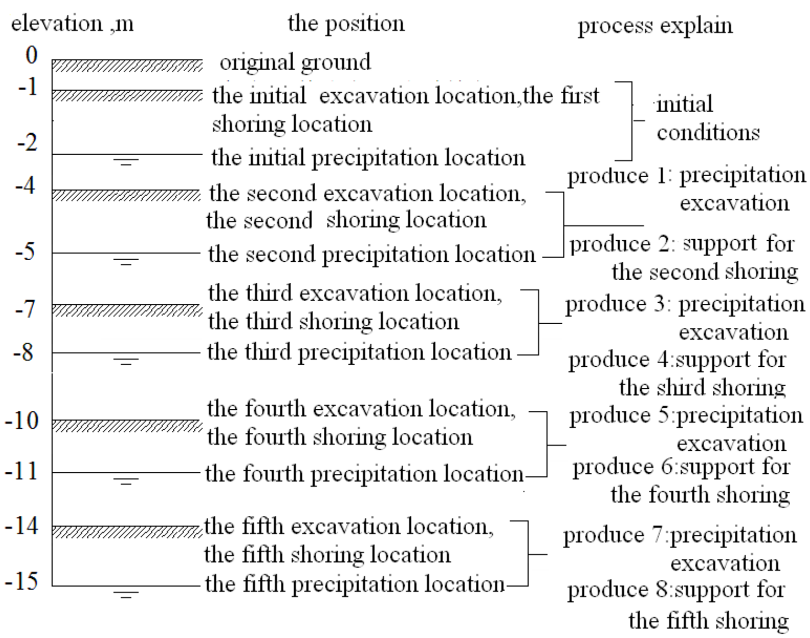

Figure 2: Plan of the basic construction procedure

About the initial pre-stress value of supporting, the regulation of the construction pit [13] suggests that pre-axial force is of 0.4 to 0.6 times than the design value. Clough pointed out that [2] if the value of lateral pressure imposed on the support was equivalent to 0.2 ~ 0.4 γ H, comprised without pre-stress, the displacement would be decreased by 50%, and it would be not significant under the limit; if the value of pre-stress was excessive, the displacement caused outward of support structure would be happened and near buildings or underground pipeline would be damaged. In this paper, considering two conditions above, the author adopted iterative method to determine value of pre-axial force. The specific practices were as follows: the initial axial force was equivalent to 0.2 γ H, and used this model to research the changes of the axial force about the first shoring in the entire process of excavation and selected the maximum value of axial force as a design value, and then amended the value of pre-axial force based on the requirement of regulation [13], and comprised the emendatory value with the value Clough proposed, if it is too small, the emendatory value was increased until it meets the requirements; if it is too much, then the value of the initial axial force was decided.

Table 4: illustration of construction processes in braces pre-stress

sequence number	Name	illustration
1	Impose pre-stress once again to the first shoring	Impose pre-axial force in the order but the first shoring, impose pre-stress to the third shoring along with the first shoring imposed
2	Impose initial pre-stress to the first shoring	Impose pre-stress in the order to all the shoring
3	Not impose pre-stress to the first shoring	Impose pre-axial force in the order but the first shoring

CHARACTERISTICS OF MODEL AND SUITABILITY ANALYSIS

The model belongs to axisymmetric plane strain problem. Model considered the change law of soil structure in the process of excavation about soft-deep foundation pit , and order change law of construction load, and change law of support structure under the different design conditions behavior. In this paper, regional comprehensive method, a modified iteration way for value of support pre-stress had been applied, and the basic conditions on excavation, conditions about pre-stress support and conditions for reference had been designed, the selection for prototype, simulation mode and simulation condition had been solved, and underground continuous wall, establishment about waterproof measures, the construction for support, imposing pre-stress(including impose once again)、excavation and precipitation layer by layer, material stiffness - stress-related properties about soil, interface attributes about soil-plate could be simulated. boards. Model parameters selected have some representation and will be able to meet design and construction requirements after referring the literature and regulation. The simulation method put forward can reflect the working characteristics of the prototype soil structure. Some types of conditions designed made comparative analysis convenient.

Relying on finite element software of PLAXIS, the model can obtain the deformation and bending curve of the wall under different conditions, the entire time - deformation curves at different shoring location and axial force changes in the value for the support system. The force and deformation for the support system can be analyzed, thereby the range and degrees of influence about the excavation also can be obtained. Through simulation we can discuss excavation depth at one-time, multi-axial force shoring design and value-added programmers (including the initial pre-value-added, and the imposition of value-added, add-time, etc.)、project monitored and control points set up, etc. These analysis methods and conclusions will be explained at another note.

The model can be applied not only to analyze behaviors of the support system of the long strip pit, but also its scope of application can be expanded after appropriate adjustments. For example, when we adopt the artificial recharge technology for ground water outside the pit to control sedimentation around the pit, water level line outside the pit can be adjusted in the process of excavation, so that they can reach initial position to simulate; if we ignored vertical deformation behavior affecting the support of the supporting column, and only analyze the central section of the retaining wall, where the stress and strain is concentrated this model established is applies to other supporting system built around pits.

CONCLUSIONS

This paper discussed the process of modeling of the pit deepened which affected the existing support structure for numerical analysis and made a number of recommendations about modeling. The conclusions and problem were as follows:

(1) To soft-deep excavation, when defined the calculation region of plane strain model, border effects, the areas of influence about excavation seepage and the influence of the built-in depth about retaining wall should be considered, The author proposes that the calculation region is not less than 2 H (deepened) at dorsal wall and calculation region is not less than 2-D (the built-in depth) at the bottom of the wall.

(2) To excavation and support of pit, H-S model is suggested as geotextile material model to simulate the relevance of stiffness and stress, which the unloading - reloading, shearing action besides the wall and arching-effect between support joints about soil can be reflected.

(3)Pre-stress value about support can be adopted by the iterative method in the model and the schedule of pre-stress imposed about multi-channel support systems should be selected after optimizing analysis. In the model, the author proposes the project of imposing pre-stress once again to the first shoring should be adopted.

(4) As used instantaneous loading and supporting treatment in this model, for excavation depth, long construction period, it does not adequately meet the requirements of precision, and therefore numerical analysis model about the process of construction period should be considered further study.

(5) Some parameters, such as vertical spacing of support, excavation depth, etc, are disposable in the process of simulation. Its limitation is obvious. Further research on the parameters may be considered in the numerical model.

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