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FLAC3D Simulation Analysis of Excavation and Supporting Structure of Deep Foundation Pit

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Abstract: The purpose of this paper is to do the simulation analysis of excavation and supporting structure of deep foundation pit by using FLAC3D to improve the structural performance. Using FLAC3D create a three-dimensional model of the deep foundation pit excavation and support process simulation analysis. Get the deep foundation horizontal displacement, settlement, vertical stress and supporting structure internal force distribution and variation. Comparing the horizontal displacement, settlement and supporting structure masterpiece of FLAC3D simulation, the deep foundation software design and site testing, the three comparison results are basically the same, that the excavation engineering instance program design rationality, numerical simulation analysis is correct. FLAC3D numerical simulation software can be reasonable for deep excavation software design based on better step excavation support deep foundation engineering simulation, to reflect the stress of the pile anchor retaining the pit during excavation and deformation characteristics, which provide guidance for the design and construction of deep foundation pit support technology, and in-depth understanding of the mechanism of pile-anchor supporting role, prior assessment of the excavation engineering in order to reduce construction the risk of an accident. Similar deep foundation also has a reference value.

Keywords: *Supporting structure; deep foundation pit; FLAC3D simulation; excavation and supporting*

1. Introduction

Nowadays, a new era of exploring the underground space has come. As both the knowledge of engineering problems and the theory research develops a lot of new excavation problems have turned up. However, the further consideration for the original questions is still being carried on. About analysis of building foundation pit and cofferdam of reservoir, it was difficult to choose constitutive model of material, and learned less about saturation-unsaturation seepage and coupled seepage and stress field as well as time-space effect. It not only had low precision and calculating efficiency in methods of inverse analysis of parameters and predicting, but also had not appropriate system and criterion of safety evaluating, thus it led to restrict the development of deep foundation pit. In order to raise the scientific of supervising the practice of deep excavation engineering, it is important to develop the study on numerical simulation of basic process and real-time optimizing. Aiming at the existent problems of the study about deep foundation pit, finite element method, time-space effect, inverse analysis of parameters, predicting, safety evaluating and so on are studied entirely merged in lots of theories and methods of FLAC3D [1].

With a great deal of tall buildings and substructures constructed, the excavations are becoming more and more. The design and construction of the excavation are becoming more and more difficult. Now, the theories and the calculating methods of protecting design for excavation in the home and abroad chiefly include the limit equilibrium method, the subgrade reaction method and the finite element method. The limit equilibrium method cannot meet engineering design demands frequently as too much factors ignored, and the application is becoming littler and littler. The finite element method is mature in theory, but it is difficult to fix the earth model and the soil parameters, so being difficulty to be practice applied. The elastic subgrade reaction method is used more and more in recent years. But the study on it is not sufficient, so the method used now cannot consider the protecting structure-soil nonlinear interaction yet. Besides, the existing means to analyse the spatial effects of deep excavation are not practical, because too complicated or too simplified.

With the emergence of the high-rise construction and the underground project, the quantity of deep foundation pit excavation project rapidly increases. The underground space took one kind not yet develops resources arouse people's widespread interest; the deep foundation pit design and the construction question become the geotechnical engineering projects hot spot. The deep foundation pit success or failure that mainly is decided by the design when soil parameter with this construction model selection whether conform to the project actual condition, the process of foundation pit excavation materially is the process of the foundation pit peripheral soil unloading, under the unloading condition the soil project of nature with the applying loading condition have wide differences [2]. Since long ago, the people adopt "applying loading" testing method definite soil parameter and constitutive model, to the design calculation structure excavation unloading soil is inappropriate obviously; carries on the foundation pit excavation with the conventional earth applying loading test parameter numerical analysis and the design calculation can have the big error inevitably. In this paper, based on the analysis of the summary of existing research results at home and abroad deep foundation pit support engineering, taking the proposed deep excavation engineering as an example, according to the process of research methods and technical route, the first application is the proposed deep foundation software for the pit supporting design. On this basis, carry on pit excavation construction and monitoring. Then on the basis of the deep excavation software design, using FLAC3D software to build three-dimensional numerical model of the excavation was simulated [4-5].

2. Analysis of the results of the research

Damage inspection, static and dynamic load tests are adopted for the deep foundation pits structures after repairing and strengthening. The results of damage inspection of the deep foundation pits structural parts show that the state of structural members is good [6-8]. However, the further consideration for the original questions is still being carried on. Slope soil stress state by the state of earth pressure at rest and gradually turned to the active earth pressure state, leading to the supporting structure inside the pit displacement, horizontal displacement of the larger sphere of influence leading to pit the ground subsidence [9]. In addition to this settlement the size of the excavation depth and scope, but also relate to the type of foundation pit, surrounded by geological conditions and the deformation size of the supporting structure. Although the excavation have been carefully designed in advance, but because of the pit there are many uncertain factors in the soil and the theory for excavation is not enough perfect, so the city started construction of the tunnel near the building ultra-deep foundation pit research is necessary.

The results of static load tests of the deep foundation pits structure show that the tested values of static structural response are less than the theoretical values, indicating that the deep foundation pit structure is important to the engineering requirements and the state of elastic working state is good, but deep foundation pit has just dynamic load test. The results of dynamic load tests analysis after repairing and strengthening processes of deep foundation pits structures show that the values of measured natural frequencies are increased and vibration frequencies are decreased.

The first type is surface damage which has surface scrapes and small nicks; this type does not need to repair. The second type is minor damage which has isolated cracks, nicks, and spalls and this type needs to repair. The third type is moderate damage which consists of concrete cracks and wide spalls exposing reinforcing steel and pressurizing strand. This type can be reduced the structure life. The fourth type is severe damage which includes exposed and damaged pre-stressing tendons and reinforcing steel along with loss of important cross section. The damages of the deep foundation pit structure can be classified as a four types [10]. Now, the theories and the calculating methods of protecting design for excavation in the home and abroad chiefly include the limit equilibrium method, the subgrade reaction method and the finite element method. The limit equilibrium method cannot meet engineering design demands frequently as too much factors ignored, and the application is becoming littler and littler. Since the sensitivity of design variables towards optimization target are abhorrent, it is difficult to establish the dominant relationships between them. The traditional fixed value analysis method has not considered the randomness of these parameters and therefore the results of this method will have some uncertainty. About analysis of building foundation pit and cofferdam of reservoir, it was difficult to choose constitutive model of material, and learned less about saturation-unsaturation seepage and coupled seepage and stress field as well as time-space effect. Reliability-based analysis method can consider the randomness of these parameters and the correlation between them fully. The first type is surface damage which has surface scrapes and small nicks; this type does not need to repair. The second type is minor damage which has isolated cracks, nicks, and spalls and this type needs to repair. Figure 1 shows a typical supporting structure of deep foundation pit and figure 2 shows an example of unstable failure for a typical supporting structure of deep foundation pit.

***Figure 1**: A typical supporting structure of deep foundation pit*

***Figure 2**: An example of unstable failure for a typical supporting structure of deep foundation pit*

3. The mathematics model and the algorithm improvement

The modeling of the FLAC3D grid was mainly with the command-driven mode. When the engineering geological conditions of the model were complicated, the efficiency to establish the3D grid model would be low obviously. AutoCAD was more difficult and time-consuming. Numerically simulation calculation with FLAC3D were decreased the difficulty. And most of the child grid needed to rebuild when model of individual control points changed. AutoCAD is not adaptable and cannot be reused and FLAC3D becomes a better tool for the engineers.

Based on the assumption of elastic-plastic model and solution of a quadratic equation, the computational scheme of UH model in FLAC3D was derived. According to the secondary developing platform, the UH model was developed in FLAC3D with Visual C++environment. Using that program, numerical simulations of triaxial compression, triaxial extension and plane strain tests were performed, which showed a good agreement with the analytic solution.

The basic algorithm for data disposal is shown in the following equations [11-14]:

$$\varphi_{ji}(\mu_j) = \exp\left(\frac{-\left(\mu_j - C_{ji}\right)^2}{b_{ji}^{\;2}}\right), \text{for } i = 1,2,\ldots,H \quad (1)$$

In this space, the m[th] multidimensional receptive-field function is defined as

$$\Phi_m(\mu) = \prod_{j=1}^{L} \varphi_{ji}(\mu_j), \text{for } m = 1,2,\ldots,N \quad (2)$$

The function can be written in a vector notation as

$$\Phi(\mu, C, b) = [\Phi_1, \Phi_m \ldots, \Phi_N]^T \quad (3)$$

Where

$$C = [C_{11}, \ldots, C_{L1}, C_{12}, \ldots, C_{L2}, \ldots, C_{1H}, \ldots C_{LH}]^T .$$

The weight memory space with N components can be expressed in a vector as

$$W = [W_1, W_m, \ldots, W_N]^T \quad (4)$$

The activated weights in weight memory space, which can be written in a vector form as

$$y = W^T \Phi(\mu) \quad (5)$$

The state variables and the desired values can be defined as follows:

$$z_1 = x_1 - y_d \quad (6)$$

And

$$z_2 = x_2 - \alpha_1 \quad (7)$$

The following tracking error dynamics is shown as:

$$\dot{z}_1 = \dot{x}_1 - \dot{y}_d = x_2 - \dot{y}_d = z_2 + \alpha_1 - \dot{y}_d \quad (8)$$

The first derivative of the Lyapunov function can be written as

$$\begin{aligned} \dot{V}_1 &= z_1^T \dot{z}_1 = z_1^T(\dot{x}_1 - \dot{y}_d) = z_1^T(\dot{x}_1 - \dot{y}_d) = z_1^T(x_2 - \dot{y}_d) \\ &= z_1^T(z_2 + \alpha_1 - \dot{y}_d) = -\lambda_1 z_1^T z_1 + z_1^T z_2 \end{aligned} \quad (9)$$

From (2) and (6), it can be obtained:

$$\dot{z}_2 = \dot{x}_2 - \dot{\alpha}_1 = -M^{-1}Cx_2 - M^{-1}(G_g + d) + M^{-1}\tau - \dot{\alpha}_1 \quad (10)$$

τ is selected as

$$\tau = -\lambda_2 z_2 - z_1 - F \quad (11)$$

Then we can get:

$$V_2 = V_1 + \frac{1}{2} z_2^T M z_2 \quad (12)$$

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 + \frac{1}{2} z_2^T M \dot{z}_2 + \frac{1}{2} \dot{z}_2^T M z_2 + \frac{1}{2} z_2^T \dot{M} z_2 \\ &= -\lambda_1 z_1^T z_1 + z_1^T z_2 + z_2^T M(\dot{x}_2 - \dot{\alpha}_1) + z_2^T C z_2 \\ &= -\lambda_1 z_1^T z_1 + z_1^T z_2 + z_2^T(-Cx_2 + Cz_2 + \tau \\ &\quad - M\dot{\alpha}_1 - (G_g + d)) \\ &= -\lambda_1 z_1^T z_1 + z_1^T z_2 + z_2^T(f + \tau) - z_2^T(G_g + d) \end{aligned} \quad (13)$$

$$\dot{V}_2 = -\lambda_1 z_1^T z_1 - \lambda_2 z_2^T z_2 + z_2^T(f - F) - z_2^T(G_g + d) \quad (14)$$

The ideal weight W from (10) and expressed as

$$F = W^T \Phi(\mu) \quad (15)$$

Define the estimate of the value of (11) as

$$\hat{F} = \hat{W}^T \Phi(\mu) \quad (16)$$

According to the effect of external load, there are three different types of stresses can be identified. These stresses are related to the nature of the deforming force applied on the body. The first type was known as tensile stresses, the second type was known as compressive stress, and the third type was known shear stress. The shear stress takes place from the force vector component parallel to the cross section. Shear stress can be obtained and the equation of motion is in the follows forms:

$$\partial_j (C_{ijkl} \partial_k u_l + e_{kij} \partial_k \varphi) - \rho \ddot{u}_i = 0 \tag{13}$$

Under the linear theory, that is:

$$\partial_j (e_{ijkl} \partial_k u_l - \eta_{kij} \partial_k \varphi) = 0 \tag{14}$$

According to the observation process for the traffic loads, there are serious overloading phenomenon exist universally when vehicles passing the deep foundation pit. The maximum vehicles weight more than 150 tons which is two times higher than the weight of live load vehicles in the design code. Serious overloading will cause large main tensile stress in the part of quartiles of middle span which leading to appear the cracks and causes the downward defection in the center of the deep foundation pit. Angular frequency can be defined as the rate of change of angular displacement (θ) during rotation. The dynamic responses include natural frequency, vibration frequency (forced frequency), damping factor, dynamic acceleration, dynamic displacement, dynamic velocity, and impact factor. The natural frequency depends on the geometry of the structure, materials properties, loads effect, extent and pattern of cracks, and effect of post-tensioning. In elastic state, the stiffness of structure in good state and the natural frequency is not equal to the zero. In plastic state, the natural frequency is equal to zero and the structure has not enough stiffness and the return period of structure would be infinity which mean if the structure subjects to a disturbance, the structure will never return to its original equilibrium state. The results of damage inspection, theoretical, and experimental analysis show that the whole structural performance of the deep foundation pit structure is not good and the deep foundation pit suffers from downward deflection which is more than the theoretical value in the center of the deep foundation pit (closure segment). The top, web, and bottom of box girders of the main spans have serious cracks which affect the structural performance of the deep foundation pit, leading to reduction the rigidity of the whole structure system. Numerically simulation calculation with FLAC3D were decreased the difficulty. And most of the child grid needed to rebuild when model of individual control points changed. AutoCAD is not adaptable and cannot be reused and FLAC3D becomes a better tool for the engineers. The appearance of cracks has significant effect not just on the deflection and redistribution of the internal forces, but also has effect on the dynamic responses such as natural frequency and damping. Progressive cracks cause to decrease the natural frequency (even by 50%) and increasing the damping properties. Figure 3 is the mesh result for a unit and figure 4 shows the result for the whole supporting structure.

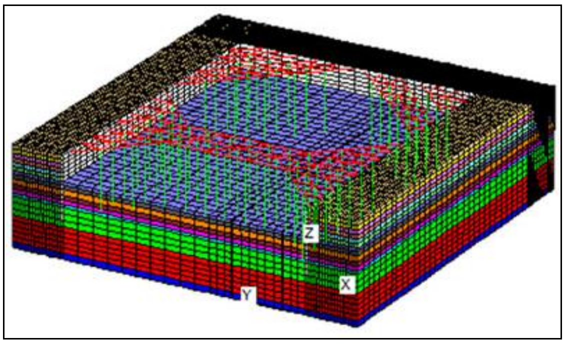

***Figure 3**: The mesh result for a unit*

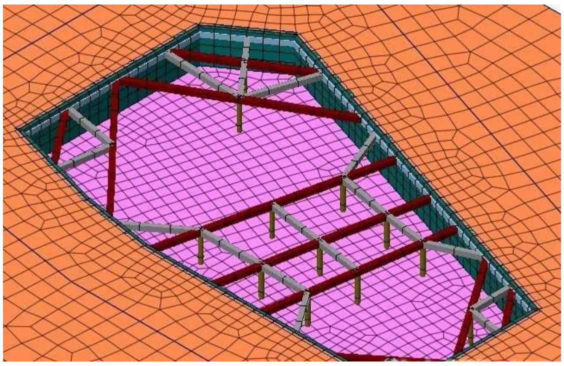

***Figure 4**: The mesh result for the whole supporting structure*

4. The experiment simulation and data analysis

According to the damage inspection process, theoretical and experimental analysis of the deep foundation pit structure, the deep foundation pit structure suffers from static and dynamic problems. In order to ensure the safety application, improve the structural performance, to reduce the vibration of the deep foundation pit, and extend the service life of the deep foundation pit structure, there is a need to repair and strengthen the deep foundation pit structure. Therefore, the service state can be recovered. The repairing and strengthening methods include repairing the deep foundation pit deck pavement, replacement of all expansion joints, treating the bearing, application of chemical grouting method for cracks, strengthening the top floor of box girders by using steel plates, and strengthening the main span of T-shape cantilever structure by using external pre-stressing tendons.

Steel plates and scattering AP resin mortar with the thickness of 10mm are used to strengthen the web and roof of box girders. Figure 5 shows the web and roof strengthening and figure 6 shows the dynamic result for the typical deep foundation pit.

The damage inspection process, field tests during inspection, static and dynamic load tests, evaluation of the structural performance of the deep foundation pits structure were described in this section. The results of damage inspection of the deep foundation pits structure shown that the structural members of the deep foundation pits structure suffers from many damages and these damages were ranged from simple to serious. There were many cracks were appeared in the different locations of the box girders of the deep foundation pits structure which were affected the structural performance and bearing capacity of the deep foundation pits structure. The maximum deflection coefficient of load test is equal to 0.59 which is near the allowable value in the Code (0.60 to 1.0), indicating that the structural stiffness of corbel is good. For typical deep foundation pit I and deep foundation pit II, the maximum deflection coefficient of load test values are equal to 1.46 and 2.49 respectively. These values are more than the allowable coefficient of load test (1.0). Therefore, the deep foundation pits structures don't meet the design requirements of stiffness and the elastic working state is not good. Therefore, the deep foundation pits structures need to repair and strengthen. Therefore, according to the evaluation factors in Chinese codes, the evaluation process shown that the deep foundation pits structure needed to repair and strengthen to improve the structural performance and to extend the service life of the deep foundation pits structures. The next chapter includes the application of repairing and strengthening methods for the damaged members of the deep foundation pits structure to improve the elastic working state and bearing capacity of the deep foundation pits structures.

***Figure 5**: The web and roof strengthening*

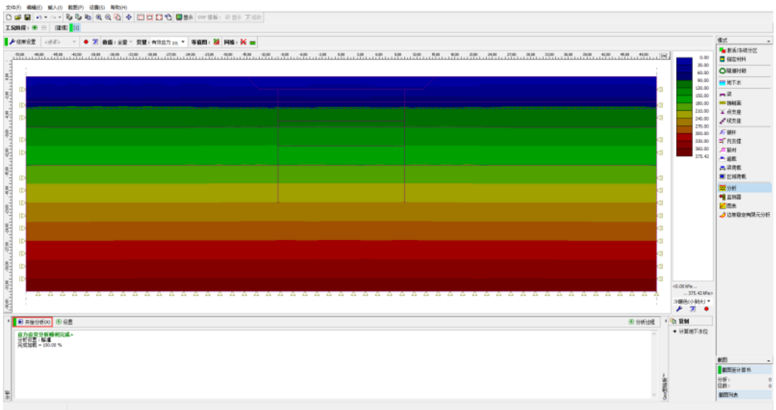

***Figure 6**: The dynamic result for the typical deep foundation pit*

The main steel reinforcement is installed in the bottom, web, and top of anchor beams. The anchor beams and the original box girder top, webs, backplane are connected together by embedding rebar. The size of anchor beam is small and it is hard to control on the quality by using normal concrete in the casting of anchor beam. Also the normal concrete cannot vibrated. Therefore, in the casting of concrete beam, self-compacting concrete is used.

The concrete surface of original box girders top, web, and backplane is removed about 2cm, and then makes lateral grooves which are not less than 3cm with width are equal to 20cm. In the middle of box girder top, hole has width 30cm carried out to inter the concrete in the mood of anchor beam and to ensure the density of the concrete.

5. Conclusions

The construction process of steel re-bars consists of three stages. The first stage is preparing the surface of box girder and marks the location of original reinforcement and tendons positions. The second stage includes drilling the holes of planting rebar and cleans the holes by using compressive air. The third stages include injecting the glue materials. By using glue guns and inserting, the steel re-bars to the bottom of the holes and connects them with the bending reinforcement of anchor beam. The purpose of this paper is to do the simulation analysis of excavation and supporting structure of deep foundation pit by using FLAC3D to improve the structural performance. Using FLAC3D create a three-dimensional model of the deep foundation pit excavation and support process simulation analysis. Get the deep foundation horizontal displacement, settlement, vertical stress and supporting structure internal force distribution and variation.

Deep excavation engineering is a huge systematic project. It is designed both to ensure the safety of retaining structure and to reduce engineering cost. The traditional fixed value analysis method has not considered the randomness of these parameters and therefore the results of this method will have some uncertainty. Comparing the horizontal displacement, settlement and supporting structure masterpiece of FLAC3D simulation, the deep foundation software design and site testing, the three comparison results are basically the same, that the excavation engineering instance program design rationality, numerical simulation analysis is correct. According to the secondary developing platform, the UH model was developed in FLAC3D with Visual C+ +environment. The damage inspection process, field tests during inspection, static and dynamic load tests, evaluation of the structural performance of the deep foundation pits structure were described in this section. The results of damage inspection of the deep foundation pits structure shown that the structural members of the deep foundation pits structure suffers from many damages and these damages were ranged from simple to serious. There were many cracks were appeared in the different locations of the box girders of the deep foundation pits structure which were affected the structural performance and bearing capacity of the deep foundation pits structure.

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