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Back analysis and safety prediction for an extremely deep foundation pit during its excavation

Analyse inverse et prédiction de sécurité d'un puis de fondation extrêmement profonde durant son excavation

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ABSTRACT
This paper is concerned with the back analysis and safety prediction of the 50m deep foundation pit for the north anchorage block of the Runyang Yangtze Bridge. The soil conditions and the design of the excavation supporting system are first briefly described. Then a three-dimensional finite element model is employed for the analysis of the system simulating its excavation and construction. Comparative studies are performed to investigate the influence of the various parameters as well as different construction procedures. Based on these analyses a practical procedure is proposed to perform the back analysis of the system parameters and the subsequent safety prediction for the next stage of excavation. Finally the actual on-site execution process is described, which shows the success of the proposed procedure.

RÉSUMÉ
Cet article se porte sur l'analyse inverse impliquée dans l'excavation de la fondation de l'ancrage du nord du Pont de Runyang Yangtze d'une profondeur de 50 mètres et prédit le degré de sécurité de la méthode de construction. D'abord sont brievement passées en revue les conditions des sols et la procédure d'excavation. Puis un modèle tridimensionnel des éléments finis est conçu pour simuler l'avancement de l'excavation durant la construction. Des études comparatives sont dans la suite effectuées pour mettre en évidence l'influence des nombreux paramètres ainsi que des differentes phases de construction. Basée sur ces résultats une méthode pratique est ainsi proposée pour effectuer l'analyse inverse des paramètres et prédire le degré de sécurité pour la phase de construction subséquante. Enfin la procédure d'excavation *in situ* est descrite, vérifiant l'efficacité de la méthode d'analyse proposée ci-dessus.

1 INTRODUCTION

The foundation pit for the north anchorage block of the suspension bridge, Runyang Yangtze Bridge linking Zhenjiang and Yangzhou in Jiangsu Province of China, is 50m in depth and 69m×55m in plan area. Obviously this is an extremely deep foundation pit rarely experienced by engineers all over the world. The construction site is located on a small island in the middle of the Yangtze River, and the subsoil is quite soft and rich with underground water. These conditions add more difficulties to the excavation of this foundation pit. Therefore it was the most difficult work in the construction of the entire bridge.

Considering the complexities and unpredictability of this deep foundation pit, extensive field observations and analyses were carried out during the excavation of this pit (Song, 2002; SGI, 2002). At each stage the observed data were analyzed to predict the safety of the next stage excavation. Back analysis herein played a very important role to obtain mechanical parameters so as to predict the deformation and inner forces for the next stage of excavation. This provided important guidance to the construction and ensured its safe completion well before the due time.

This paper summarizes the aforementioned work, with special attention being paid to the back analyses and safety prediction. The soil conditions and the design of the excavation support system are first briefly described. Then a 3-D finite element model is proposed for the analysis of the support system simulating its excavation and construction. Based on comparative studies on the influence of various parameters a practical procedure is proposed to perform the back analysis of the system parameters and the subsequent safety prediction for the next stage excavation. Finally the actual on-site execution process is described, which shows the success of the proposed procedure.

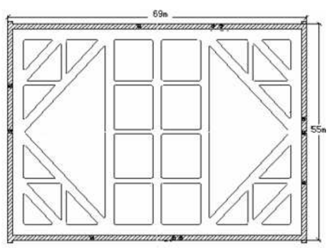

Figure 1. Plan of the pit with the strut system

2 GENERAL DESCRIPTION OF THE PROJECT

The north anchorage block is located on a small island in the Yangtze. The soil of the upper 14~18.8m is mainly silty clay at flowing plastic state, and further below till a depth of about 50m is mainly fine sand layer at slightly dense to medium dense state. Below the depth of about 50m there is granite at different degrees of weathering and integrality. The underground water level is close to the ground surface, and it is rich in quantity.

The plan of the foundation is designed to be a rectangular shape. The support system consists of diaphragm walls and internal struts made of reinforced concrete. The outer dimension of the diaphragm wall is 69m×50m. The thickness of the wall is 1.2m, embedded in the rock for a certain depth. The embedment depth for strongly weathered, moderately weathered and slightly weathered rock is respectively 6m, 3m and 1m. In the original design there were 12 levels of internal struts. In the actual construction the 12^{th} level of struts was left out due to the relatively large fluctuation of the bottom rock surface. At the same time the 11th level of the struts was strengthened and moved slightly downwards. The shape of the internal struts is as shown in Fig. 1, the periphery beam is of a width of 2~3m, and the width of the internal bars is either 2m or 1m. The heights of the cross section of the periphery beam and the internal bars are 1-1.5m. The first level of struts is 1.5m below the surface, the lowest level of struts is about 1.9m above the pit bottom. The spacing of the adjacent layer of struts is about 4m. At the cross points of the supporting bars, piles were constructed before the excavation started in order to support the weight of those struts and to ensure their stability.

Besides, surrounding the foundation pit, 23m away from the diaphragm wall, a watertight curtain was constructed by spin jet grouting. In between the curtain and the wall, some wells were constructed for lowering the water level when the excavation was reached relatively great depth. A rough rule was to keep the difference between the internal and external water level within 30m. The internal water level was lowered with the proceeding of the excavation.

3 BACK ANALYSIS AND SAFETY PREDICTION

In order to insure the safety during the excavation, field observation and safety prediction during the construction was absolutely necessary. For this project, both the ANN (artificial neural network) method and the finite element method were employed for this purpose. The ANN method is relatively simple and suitable for quick response at construction site. But it can only give predictions for a limited number of points in the system. The FE method is time consuming, but it can provide deformation and inner forces within the entire system, and consequently it is facilitate thorough analyses of the system and discover possible failures. In the following, main attention is paid to the FEM.

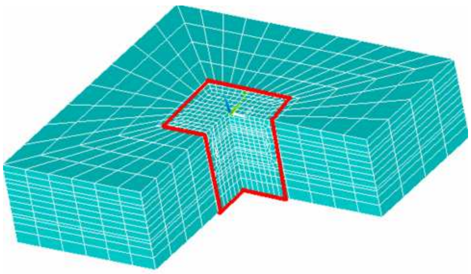

Figure 2. The finite element mesh

3.1 *The finite element model*

In order to better simulate this deep excavation system, the soil-structure model was used, namely the supporting structure and the soil were seen as one system, so that the interaction between them and the staged construction could be considered. Moreover, the space effect must be considered for this project since the depth is of the same order as the plan dimensions. Hence, three-dimensional model was employed.

In this project the finite element software ANSYS was used for the three-dimensional analyses. Fig. 2 shows the finite element mesh. The entire foundation pit was taken for the analysis in order to consider the asymmetry in the system parameters and excavation sequences. The vertical boundary was located at a distance of two times the excavation depth from the side of the foundation pit. The bottom boundary was 30m downwards from the pit bottom. Since it is rock layer below the bottom, 30m below the bottom should be enough. In this model, 20-node volume elements were used for the soil and rock layer, 8-node shell elements for the diaphragm wall, and 3-nodel three-dimensional beam elements for the enclosing beam and struts. Considering the capacity of the computer, relatively coarse mesh was used for the mesh outside the pit area.

Table 1. The first estimation of the soil and rock parameters

Layers	E (MPa)	γ (kN/m^3)	ν	C (kPa)	φ (°)
silty caly 1	3	18.1	0.35	25	5
silty caly 2	8	17.9	0.35	20	9
silty sand 1	15	19.0	0.30	10	27
silty sand 2	30	19.0	0.30	10	30
Rock (WM)	3000	22.0	0.25		
Rock (WS)	50000	22.0	0.25		

Note: WM stands for "moderately weathered", WS for "slightly weathered".

The stress-strain relationship of the soil was modeled by using the Drucker-Prager model, and the concrete by a bilinear hardening model. The soil was basically divided into 4 different layers, i.e. the approximately 16m thick clay layer below the ground surface and the 32m thick sand layer below were both divided into two sub-layers. The estimated soil and rock parameters according to the ground investigation are listed in Table 1. In theory, the cohesion of sand should be very small, but considering the fact that partially saturated sand should have certain cohesion, 10kPa was used in the calculation. This facilitated the calculation and this is also more close to reality. These values were only a first estimation. Better model parameters would be re-calculated through back analysis according to the measured deformation and inner forces in the supporting structure during the excavation.

3.2 *Study on the back analysis method*

3.2.1 *Sensitivity of influence parameters*

As there are many parameters in the system, we could not expect to back-analyze too many of them. We should catch those parameters that were hard to estimate and had strong influence on the results. Therefore, comparative studies were first carried out to investigate the influence of various parameters and construction procedures, such as first excavation then support, first support then excavation and excavation and support concurrently. Some main results are given below.

(1) The influence of the rock modulus

The caculation results revealed that the mudulus of the rock layer had a trong influence on the bending moment in the wall at the clamped end. The bending moment incresed as the mudulus of the rock layer increased. But the influence to the upper part was relatively small. The influence on the deformation was also linlimited to the bottom and it was relatively small. Besides, the rock modulus had also some influence on the inner forces in the lower levels of struts.

Based on these analyses we might conclude that the back analysis of the rock modulus should be done according to the change of the bending moment and strut force in the lower part.

(2) The influence of the Poisson's ratio of the soil

Calculations with different values for the Poisson's ratio of the 4 soil layers had been performed. The results showed that the Poisson's ratio of the third layer had the most pronounced influence on all the main response of the system, including the wall displacements and bending moments, as well as the strut forces, whereas the Poisson's ratio of the other three layers has just minor influence. Based on these analyses, much attention should be paid to the third layer of the soils during the back analyses.

(3) The influence of the soil and strut rigidity

It is found that the influence of the modulus of the concrete and the first two layers of the soil was insignificant. Consequently, it was not the main point of the back calculation. But the modulus of the third and fourth layer had pronounced influence, especially the fourth layer. Therefore, much attention should be paid to the moduli of these two layers.

(4) The influence of the excavation sequence

Two extreme cases were taken to do the analyses and the results were compared with the standard case. The two extremes were:① excavation before support, namely a layer of soil is first excavated, then the struts were constructed; ②support before excavation, namely the struts were first made active and then a layer (corresponding to the vertical spacing of struts at two adjacent levels, about 4m) of soil was excavated. The calculations showed that for the first case the horizontal displacements and the bending moments in the wall were significantly larger, and the forces in the struts were smaller; for the second case the phenomenon was on the contrary. If the support was constructed concurrently with the excavation, the results were somewhere in between.

Based on the analyses, we could see that the construction sequence had the strongest influence, and the Poison's ratio and modulus of the third and fourth layer had relatively large influence on the displacements than on the strut force. The rock modulus had large influence on the bending moment at the camped end of the wall. Hence, we chose these parameters to be back-calculated from the measurements.

3.2.2 *The method used for back analysis*

Based on the studies above, the soil and structure parameters were divided into the following three categories: ①Parameters which could be determined from available data, for instance the unit weight of material and the concrete modulus; ② Parameters which could be determined according to the in-situ measurements instead of back-analyses. For instance, the Poison's ratio could be determined from the measured soil pressure. The measured soil pressure at the beginning could be seen as static pressure. In the calculation model of ANSYS, the static soil pressure depends on the soil weight and the Poisson's ratio. Therefore, the Poisson's ratio can be estimated from the measured soil pressure. (This is only valid when using ANSYS.) ③Parameters which should be determined through back analyses, which included the soil moduli and strength parameters, and also the construction sequence, namely to adjust the sequence of activating of strut elements, de-activating soil elements and lowering the water level, so that the real process was simulated.

In order to better simulate the actual mechanical process of the construction, we carefully observed the construction procedure on the site, observed the development of the rigidity of the RC struts, and then determined the actual construction process. For instance, the struts in the middle could be constructed before the soil at its two sides was excavated. But, as some time was needed before the struts gained strength and rigidity, the excavation of the soil at its two sides and the construction of the struts could be seen as happening at the same time, or even the construction could be seen as happening later than the excavation.

Careful consideration was also necessary for the mechanical parameters of the system, so that a really correct strategy was chosen for the back analysis. For instance, as the first two soil layers were at a smaller depth and the immediately support restrained their deformation, they were basically in elastic state. Hence, it was not necessary to back calculate their strength parameters, at least for the early period. On the contrary, great attention must be paid to the back analysis of the strength parameters of the third soil layer.

The direct method (see e.g. Zhu & Shen,1990) was employed for the back analysis, namely a combination of the finite element analysis and the optimization method was applied. The true model parameters should be those that make the following target function a minimum.

$$J = \sum_{i=1}^{m} W_i \left(\frac{S_i}{S_i^*} - 1 \right)^2 \rightarrow \min$$

where m is the number of measured values, S_i^* is the number i measured value; S_i is the corresponding calculated values, W_i is the weight factor for the number i value.

The weight factor is introduced in order to consider the different degree of influence and different reliability of different parameters. Larger weight factors were employed for the displacements.

As there were a large number of measured data, not all them should be used in constructing the target function. Instead it was better to use those data which were sensitive to the to be back analyzed parameters. For instance, there were a vast number of data for the lateral displacements of the wall measured by using inclinometers. But we used only the displacements in a relatively small region containing the point with the maximum displacement.

Optimization was needed in the back analysis. There are many optimization methods available. The conventional methods usually need less iteration, but they may be trapped into local optimum. Some newly developed iIntelligent methods, such as the heredity method and the artificial neutral network method, can in theory give global optimum, but they may be very time consuming. This paper proposes to use the conventional complex method combined with some experiential adjustment, so as to fulfill the need of quick response on the site.

The complex method is an optimization algorithm developed from the simplex method. It can select and improve the design point in the n-dimensional space with nonlinear constrain conditions. Limited to the length of the paper the details will not be discussed here. The interested readers may refer to some text books on optimization (e.g Chen, 1991). Although this method has the same shortcoming as other conventional optimization method, i.e. sometimes it may fail in finding the global optimum. But for a specific engineering project, we have the soil parameters given by ground investigation report as a first estimation. Besides, comparative studies also help to locate the design space. All of these facilitate an efficient and reliable global optimization. The engineering practice in this project also approved the above arguments.

For a complex problem as this foundation pit, where the construction process, the space effect and the non-linearity and so on were all to be considered, and the safety prediction for which should be given in a short time, it is not enough just use the conventional optimization method. A better policy is to combine the theoretical method with some experiential adjustment. The following procedure was proposed:

① Some parameters could be estimated first according to the soil investigation, and the Poisson's ratio can be determined from the measured soil pressure. The construction sequence was approximately simulated based on careful observation on-site. Then the finite element calculation can be performed.

② Compare the calculation results with the measured data. According to the deviation, choose the relatively influential parameters and adjust their value by the complex method.

③ According to the findings by the above comparative studies, make further adjustment to the parameters, then perform the calculations again.

④ Repeat the above procedure till the difference between the calculated values and measured values was smaller than an acceptable value.

As mentioned above, the construction procedure could only be modeled by using a discrete process. It could be done only by manual adjustment of the calculation model according to the on-site construction process and the qualitative judgment. Combined with back-analysis of the soil and rock parameters, the calculated results could approach quickly to the measured values.

3.3 *The application of the back analysis method*

In this work we started the back analysis from the beginning of the excavation and safety prediction was give since the third level of struts were constructed. The actual back analyses were performed as outlined above.

The support system performed quite normal till the 6th level of struts was constructed. However, the deformation of the wall increased rapidly by 29mm, which was the sum of the deformation of the previous several stages. At the same time the point with the largest lateral displacement also moved from -20m to -24m. There was also abrupt change in the bending moment of the wall at the clamped end.

After careful analyses of the above phenomena, it was concluded that plasticity occurred in the wall. Back analysis also showed that the plasticity of the wall must be considered in order to get better agreement between the calculated and measured values. Although the plastic regional was not yet large, we proposed to lower the water level outside the pit for a few meters in order to insure the safety of the support system.

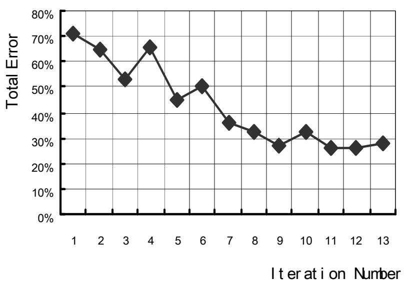

Figure 3. The change of the total error with iterations

With the depth of the pit increasing, more levels of struts were constructed. When the depth was approaching to the bottom, the struts already in place could give enough support, and the bottom was competent rock layer. Therefore, the system became stronger then its early period. By further analyses, and considering the uneven top surface of the rock layer at the pit bottom, it was suggested that the 12th layer of the struts could be left out and at the same time the 11th layer of the strut be strengthened and moved a little bit lower.

By the end of April, 2004, the excavation was successfully completed. The support system worked quite well. The maximum lateral displacement on the wall is just bout 140mm that is less than 0.3% of the pit depth. The construction period had also been cut short by about one month.

The back analyses showed that the proposed strategy is rational and practicable. As examples, Fig. 3 shows the change of the total error with the iterations. Fig. 4 compares the predicted wall displacements with the measured values. The agreement is quite satisfactory.

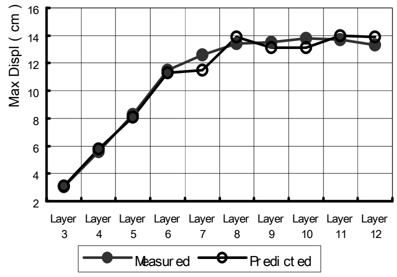

Figure 4. Comparison of the measured and predicted maximum displacements

4 CONCLUDING REMARKS

Relying on informative construction techniques, the extremely deep foundation pit in the Runyang Yangtze Bridge engineering project has been well completed. Through this work, the following can be concluded: ①It is both necessary and applicable for important engineering project to employ finite element back analyses and safety predictions; ② To do finite element analysis for a complex project, one need to be familiar with both the finite element method and the engineering project; ③ For doing on site 3-D finite element analysis quickly for a large project, one cannot yet rely purely on mathematical method. Instead, one needs to compose some effective method according to the problem to be analyzed. ④The method proposed in this paper seems to be an acceptable method.

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