Deformation monitoring and numerical simulation analysis of ultra-deep working well

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Abstract. Taking an ultra-deep working well in Jinan as the background, a three-dimensional finite element model of the excavation of the foundation pit was established using nonlinear finite element analysis software MADIS GTS /NX. The numerical simulation of the excavation process of the foundation pit, combined with the actual measured data, studied the deformation law of the envelope structure under the "underground continuous wall and internal support" support scheme. The results show that the three-dimensional finite element model can better consider the influence of the spatial effect of the foundation pit on the underground continuous wall and the surface deformation around the foundation pit. The calculated value and the measured value have a small gap, and the development trend is almost consistent. The optimization design and deformation control of the supporting structure of the project provide a basis and also have reference value for the design and construction of similar projects.

1. Introduction
With the continuous development of China's cities, underground space has been continuously developed and utilized, and a large number of deep foundation pit projects have appeared in the process[1-3]. The scale of foundation pits is getting bigger and bigger, and the depth is getting deeper and deeper, so the excavation and support of deep foundation pits have become hotspots and difficulties. The deformation caused by the excavation of the foundation pit poses a threat to the surrounding buildings, so the deformation of the foundation pit during the construction period has become a concern of many design and construction units [4]. More and more relevant professionals will combine monitoring and measurement with computer technology to study the process of foundation pit construction. Deformation situation, to be able to better manage the foundation pit project and strengthen safety measures. For example, Fang Shijun [5] summarized the deformation law of the retaining structure of the subway deep foundation pit at different excavation stages using Lizheng numerical simulation software and FLAC2D software simulation method. And the maximum horizontal displacement occurs at 2/3 of the excavation; Guo Yugen[6] used ANSYS simulation and monitoring results to compare and analyze, and obtained the law of soil layer change and stress distribution law of supporting structure during the excavation of deep foundation pit; Feng Xiaola [7] used the finite element software PLAXIS to carry out a numerical simulation analysis of the whole process of excavation of the deep foundation pit of the old commercial and residential project in
Wuhan Li Siwei [8] Using PLAXIS 3D Foundation finite element software to model the displacement of the pile and the top of the retaining pile, the axial force of the steel support, and the surface settlement of the soil around the foundation pit during the excavation of a deep foundation pit in Beijing subway analysis. With the rapid development of finite element theory and computer technology, numerical simulation has become a powerful tool for underground engineering construction research[9]. It is more important to numerically simulate the foundation pit before excavation, which can effectively reduce engineering accidents happened.

Based on the foundation pit project of an ultra-deep working shaft in Jinan, this paper uses MADIS GTS/NX to simulate the entire process of excavation. The simulation results are compared and analyzed with the field monitoring data, and the deformation laws of the soil layer and the retaining structure in the excavation of foundation pits are obtained, in order to play a certain reference role for the monitoring of foundation pit projects in similar areas.

2. Background

2.1. Engineering hydrogeological conditions
The upper part of the fourth layer of the site is artificial filling, the cause of the river alluvial powder, sticky soil, the middle is the sticky soil, powder soil, sandy soil of the pre-mountain alluvial cause, and the hui long rock invaders of the sub-generation Yanshan period. The main formation rock nature description is shown in Table 1.

| Serial number | Item     | Side pressure factor (K0) | Bulk density γ(kN/m3) | Compression modulus Es (MPa) | Cohesive force c(kPa) | Internal friction angle φk(°) |
|---------------|----------|---------------------------|-----------------------|--------------------------------|-----------------------|-----------------------------|
| 1             | Silt     | 0.43                      | 18.3                  | 10                            | 22                    | 18                          |
| 2             | Silty soil | 0.3                       | 19.4                  | 12                            | 15                    | 22.5                        |
| 3             | clay     | 0.43                      | 19.6                  | 16                            | 15                    | 16                          |
| 4             | fine sand | 0.25                      | 21.2                  | 50                            | 2                     | 32                          |

2.2. Foundation pit support form and monitoring

The length of the shield-originating working well pit was 152.2m, the width was 34.14m to 50.0m, the bottom plate was buried at a depth of about 26.2m-31.0m, and the thickness of the main top plate covered was about 3.0m. Using the method of clear excavation, the main enclosure structure of the base pit is supported by 1200mm underground continuous wall, the depth of the underground continuous wall is 47.0m-51.5m, and the support cross-section is 1.2m×1.2m and 1.2m×1.5m. Underground continuous wall using underwater C35 reinforced concrete. The steel support is 800mm steel pipe with an internal diameter, the wall thickness is 20mm, and According to the design and specification requirements of the construction drawing: the main monitoring point layout section on the site as shown in Figure 1.
3. Establishment of a three-dimensional finite element model

3.1. Establishment of the calculation model

In this paper, the finite element software MIDAS GTS/NX is used to expand the numerical analysis. The model size is: \(L \times W \times H = 330\text{m} \times 250\text{m} \times 90\text{m}\). The calculation model is shown in Figure 2 and Figure 3. Horizontal and vertical displacement constraints are applied at the bottom of the model, horizontal displacement constraints are applied horizontally, and the upper surface of the model is set as a free surface without any constraints.

![Figure 2. 3D computing model](image)

![Figure 3. Foundation pit retaining structure model](image)

For the convenience of calculation, the following assumptions are made in the analysis:

1. select MohrCoulomb constitutive model, simulate the soil by the solid element, simulate the bolt with embedded truss, and simulate the tunnel segment with plate element.

2. the same layer of soil is homogeneous and continuous and has the isotropic.

3. the effect of groundwater is not considered.

3.2. Simulation of construction conditions

Before excavation of the foundation pit, the in-situ stress balance is carried out, and then it is used as an underground continuous wall. Excavation of foundation pits is carried out in accordance with the principle of "layered excavation, with excavation and bracing", excavation to 1.2m → erecting the first concrete support → excavation to 6.2m → erecting second concrete support → excavation to 11m → Erecting the third concrete support → Excavation to 14.5m → Erecting the fourth steel support → Excavating to 17m → Erecting the fifth steel support → Excavating to 22.6m → Erecting the sixth support → Excavating to 27m → Erecting the seventh support → Excavating to the base.

3.3. Numerical simulation results

Figure 4 is the vertical displacement cloud after the excavation of the foundation pit. It can be seen from the figure that after the excavation of the soil body, the original initial stress balance field is broken, the internal force is redistributed, and the formation around the pit settles down. As the excavation depth of the foundation pit continues to increase, the settlement becomes larger and larger, and its value gradually decreases as the distance from the foundation pit increases, until it is zero at a farther distance, and there is a significant uplift at the bottom of the pit.

Figure 5 is the cloud diagram of the displacement of the envelope structure after the foundation pit is excavated. It can be seen from the figure that the horizontal displacement curve of the supporting structure exhibits a small "big" bow shape on both sides, and the location where the maximum displacement occurs is about 2/3 of the excavation depth of the foundation pit, and the maximum displacement value is 62.43 mm.
4. Comparison of field monitoring and numerical analysis

4.1. Surface subsidence

Due to a large number of surrounding ground subsidence measuring points, the representative DBC22 measuring point data is given here. And put forward the surface settlement data in the same position as the model. According to the three key working conditions, the field measured data is compared with the numerical simulation calculation results to obtain the surface deformation during the excavation of the foundation pit, as shown in Figure 6.

It can be seen from Figure 6 that as the excavation depth of the foundation pit increases, the settlement deformation also gradually increases, and decreases with increasing distance from the edge of the pit, and eventually tends to be stable. Its shape is similar to a "spoon shape". The actual settlement of the monitoring point DBC01 is greater than the simulated value. The maximum cumulative settlement value of the simulated value after the excavation of the foundation pit is 24.94mm, about 0.08% H, appears outside the pit at about 0.16H, and the impact range is about 1.28H. The maximum cumulative settlement value of the measured data is 60.46mm, about 0.19% H, appears at about 0.301H outside the pit, and has an impact range of about 1.28H. Although the results are inaccurate, the calculated value of the maximum settlement of the ground around the foundation pit is generally similar to the monitoring value.

4.2. Deep horizontal displacement

The calculation results of the deep horizontal displacement monitoring point ZQT01 under the three key working conditions are compared and analyzed with the actual measured values. The comparison curve is shown in Figure 7.

It can be observed from Figure 7 that with the excavation of the foundation pit, the horizontal displacement of the retaining knot gradually increases, and finally shows a deformation trend of "small at both ends and large at the middle". When the soil is excavated to 11m, the measured value reaches the maximum at a wall depth of about 10m, and the simulated value reaches the maximum at 0.5m at the upper part of the wall; when the soil is excavated to 22.6m, the wall depth is 14~14.5m, the simulation curve has a significantly reduced inflection point, and the measured value is always in a state of gentle decline. When excavating to the bottom of the pit, the maximum horizontal
displacements of the measured and simulated values are 22.96 and 22.13mm respectively, each accounting for 0.073% and 0.071% of the maximum excavation depth, both of which are within the monitoring measurement standard range (30mm). The monitoring results of ZQT01 are slightly different from the numerical simulation, and the reasons are analyzed: the numerical simulation cannot take into account the many influencing factors encountered in the actual construction process, such as mechanical vibration, inadequate support during the construction process, and inadequate drainage and drainage work on the construction site. In place, etc. will cause the displacement of the monitoring results to increase. It can be seen that there must be some inevitable errors between the calculation results and the monitoring results, but the changing trend of the calculation results and the monitoring results is the same, indicating that the calculation model, calculation method, and calculation parameters of the numerical simulation analysis are feasible, and also prove that the numerical simulation analysis can indeed reasonably reflect the deformation characteristics of the foundation pit and provide a reliable theoretical basis for the design of deep foundation pit engineering.

5. Conclusion
In this paper, a threedimensional numerical simulation of the foundation pit of an ultra-deep working well in Jinan is carried out by using the finite element method, and the following conclusions are drawn:

(1) By comparing the calculation results with the monitoring results, the results show that the basic trends of the deformation of the underground continuous wall and the surface deformation around the foundation pit are generally consistent. It shows that the finite element calculation model, parameter selection, and equivalent replacement are reasonable, and the numerical calculation method can provide scientific guidance and theoretical basis for the design and construction of foundation pit engineering.

(2) The surface settlement around the foundation pit is related to the distance from the measuring point to the edge of the foundation pit. With the excavation of the foundation pit, the surface settlement of the adjacent soil gradually increased, and then gradually stabilized. The settlement gradually increases outward from the edge of the foundation pit, and then gradually decreases. The maximum settlement value appears at a certain distance from the edge of the pit, presenting an obvious "scoop-shaped" groove.

(3) The horizontal displacement of the supporting structure is closely related to the depth of construction excavation. When the deep foundation pit cantilever is excavated to a certain depth, the horizontal displacement curve of the supporting structure is forward-tilted, and the horizontal
displacement of the upper part of the wall. The maximum value; with the erection of internal support, the application of prestressing and the further excavation of the foundation pit, the horizontal displacement curve of the supporting structure gradually changes to the "bow" shape and the location where the maximum displacement occurs also moves down 2/3 of the excavation depth of the foundation pit. The change curve of the horizontal displacement of the wall with the increase of the excavation depth of the foundation pits shows a fast first, then slow, first steep, and then slow, indicating that the support has a good control effect on the horizontal displacement of the wall.

(4) The actual project is affected by the surrounding environment, variable loads, construction machinery, and space-time effects. The existing numerical simulation methods cannot be considered comprehensive, making the calculated value slightly smaller than the monitored value. How to improve calculation accuracy and authenticity is a problem that needs to be solved in the future.

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