DOI 10.15302/J-SSCAE-2017.06.016

Research and Trends in Environmental Effects of Urban Excavation in Underground Engineering Development

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Abstract: With the increasing developmental scale of urban underground space, the main challenge of urban underground space development has gradually shifted from the stability of the foundation pit to deformation control of the environment around the foundation pit. Underground space development in a complex environment may easily lead to uneven surface subsidence and building cracking, resulting in great economic losses. Therefore, the environmental effect of various excavation foundation pits and environmental effect control technology must be systematically studied. This paper introduces and reviews the application of statistical, numerical simulation, and model test methods in the study of the environmental effects caused by excavation foundation pits. This paper also summarizes the advantages and disadvantages of each research method, introduces the existing environmental control technology and application cases, summarizes the research results on the environmental effect of underground space development, and proposes some suggestions for future research in this field.

Keywords: underground space; excavation; foundation pit; environmental effects; deformation control

1 Introduction

China has been developing urban underground space since the 1980s. After 30 years of progress, the development of underground space has entered a period of high-speed development, in which complex urban underground synthesis is developing at a breathtaking pace. Taking the development of underground space in Zhejiang Province as an example, by the end of 2012, the development area of underground space in Zhejiang Province was 12181.9×10^4 m^2, and the built-up area of underground space was more than 1×10^6 m^2 per year [1]. In recent years, a wave of subway construction has emerged in China. As of July 2017, 32 cities in China have launched urban rail transit systems, with a total mileage of 4452 km. Among them, the operation mileage of Shanghai and Beijing has exceeded 600 km, and their operating scale lies in the first and second place in the world.

The development of urban underground space shows a trend of getting longer, larger, and deeper. As the depth and area of excavation increases, the surrounding environmental problems caused by the development of underground space are attracting more and more attention. The development of deep underground space will cause changes in the surrounding strata, resulting in uneven settlement and cracking of existing buildings, underground pipelines, and shield segments, which will affect the normal function of various kinds of building structures and may even affect their structural safety. Therefore, scientific and rational planning, design, construction and monitoring control standards are needed to ensure the reliability of environmental impact during the development of underground space and to ensure that the surrounding buildings, roads, and underground pipelines are in a safe and available state.

Received date: December 6, 2017; **Revised date:** December 20, 2017

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Funding program: CAE Advisory Project "Strategic Study on Urban Underground Space Development" (2015-XZ-16)

Chinese version: Strategic Study of CAE 2017, 19 (6): 111–115

Cited item: Zhu Yihong et al. Research Status and Trends of Environmental Effects of Urban Excavation Underground Engineering Development. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2017.06.016

2 Research on environmental effect of underground excavation

The main challenge of underground space development in China has gradually shifted from the stability problem of early subterranean works to the control of deformation in the surrounding environment in underground engineering.

Underground excavation in China mostly takes place in the downtown areas of cities. Foundation excavation often affects the surrounding important buildings, municipal roads, underground pipelines, subway shields, and other facilities. This changes the original ground stress field, causing displacement of the surrounding strata and leading to uneven settlement of the surrounding construction.

2.1 Statistical and empirical method

Peck [2] first carried out systematic research on the deformation of foundation ditches. He proposed an empirical estimation method for ground settlement and distribution considering stratum difference.

On this basis, scholars have divided the deformation area of foundation ditches into the main influence area and the secondary influence area and have discussed the deformation characteristics and the boundary of the strata in the two regions. Through continuous analysis of deformation monitoring data of foundation pits, scholars have put forward the empirical formula of foundation pit deformation considering various factors and have evaluated the stability of foundation pits with the parameters of foundation pit bottom uplift and ground wall settlement after a retaining wall.

Brand et al. [3] systematically summarized the main factors affecting the deformation of the foundation pit supporting system, including the following: ① the type of support, ② the stiffness of the supporting system, ③ the buried depth of the retaining wall, ④ the pre-loading value, ⑤ the excavation exposure time, ⑥ the construction method of main body, ⑦ the overloading value upon the surface, ⑧ the shape and depth of excavation, ⑨ the characteristics of the foundation soil, and ⑩ the foundations of the surrounding buildings.

Through monitoring statistics, the deformation of foundation pits has significant spatial and temporal effects. The larger the exposed area of foundation soil and the longer the exposure time, the greater the increase in deformation. In particular, in the soft-soil areas of the southeast coast of China, which is economically developed, soil creep can account for 30% to 60% of the total deformation. Therefore, controlling soil creep in soft soil is very important to control the total deformation of foundation pits. Supporting structures that provide support after excavation can effectively control the creep of foundation soil.

The statistical empirical method is based on the actual observation of the influence of foundation pit excavation on the surrounding formation disturbances; thus, the formation changes and main influencing factors can be elucidated. Owing to the actual engineering situation and the site layout of measuring points, generally only parameters such as ground settlement around the excavation, deformation of the envelope structure, and uplift of the bottom of the pit can be obtained as indicators of the characterization. Combined with engineering geological conditions and supporting forms for analysis, we cannot obtain a complete ground deformation field.

2.2 Numerical simulation methods

With the rapid development of computer science, numerical simulation methods have been incorporated into the traditional engineering design process. The numerical simulation of excavation can better consider the constitutive characteristics of rock and soil, engineering geological conditions, the interaction between structure and soil, and the relationship between the contact surface and the complex excavation conditions. Therefore, increasing attention has been paid to the field of deformation prediction in underground engineering.

Duncan et al. [4] used a nonlinear elastic model to simulate the shape of the slope excavation, and they created a precedent for numerical simulation of the deformation involved in underground engineering.

The numerical simulation method can consider the fluid–solid coupling problem in the deformation of underground engineering, and various complicated constitutive models can be applied to simulate the stress–strain behavior of soil. After Duncan-Chang's nonlinear elastic model, various models including the Mohr-Coulomb, Mises, and Cambridge models, a modified Cambridge model, and a hardened soil model were applied to the research of underground engineering deformation. The abundant constitutive model can be used to simulate the deformation behavior of rock and soil under various stress paths and working conditions.

The early numerical analysis method simplified the three-dimensional problem as a two-dimensional problem to be solved. Two-dimensional numerical analysis can simulate the excavation of a tunnel section and a rectangular foundation pit with a large aspect ratio. In recent years, with the continuous enhancement of computing capabilities, three-dimensional numerical simulation methods have gradually matured. Those studies have found that two-dimensional analysis, which selects important sections for deformation prediction simulation, predicts larger deformations than three-dimensional simulation and actual monitoring [5]. The three-dimensional numerical simulation method can better analyze the ground deformation caused by irregular underground engineering.

The numerical simulation method can simulate the deformation properties of underground engineering under various boundary conditions and various conditions at low cost. There are many influencing factors in the deformation of underground excavation and many combinations of working conditions. Numerical simulation methods can be studied by setting various combinations of variables. Rowe et al. [6] considered the influence of several factors, such as stratum loss and grouting on the tunnel excavation, based on the anisotropic elasticity assumption of the soil, and introduced gap parameters so that the influence of various construction factors can be considered when the subsidence is calculated.

The numerical simulation method can simulate the geotechnical media, excavation conditions, and boundary conditions well, and can consider the influence of the seepage field and temperature field, so it has obvious advantages over traditional calculation methods. However, the domestic numerical method has a shorter application time, the empirical accumulation of methods and engineering parameters is little, and further application and accumulation are needed to ensure the rationality of parameter selection in numerical analysis. Numerical simulation is unsuitable in certain construction situations, including disturbances caused by the construction of the envelope structure, disturbances caused by pile replacement, and so forth.

2.3 Model test methods

The model test method is an important method to study and verify the geotechnical engineering theory. The early indoor model test mainly studied the stability and deformation mechanism of the excavation of the foundation pit and achieved fruitful results. In recent years, foundation pit deformation has become the main research focus. A small-scale model cannot effectively simulate the stress field of the foundation soil. Large-scale model test conditions and costs are high, so the centrifuge model test has been rapidly developed.

As early as 1948, Terzaghi et al. [7] used an indoor model test to study the relationship between the wall pressure, wall deformation, and earth pressure as well as the wedge angle of sliding wedges of bulk materials.

Indoor small-scale testing focuses on the effects of changes in soil properties after the wall and changes in the contact conditions between the wall and the soil on the earth pressure during the excavation of a foundation pit and changes in surface settlement behind the wall. The stress field and deformation field in a small-scale test cannot completely simulate actual working conditions, and only qualitative research on the influence factors of foundation pit deformation can be performed.

The centrifuge test can better simulate the stress field, ensuring that the stress conditions in the area of the model box are close to the actual working conditions suitable for destabilization failure testing. Thus, a better simulation can be achieved of the trend of changes in the stress and deformation of the foundation and wall under various working conditions of foundation pit excavation.

Large-scale testing can better simulate the stress field and deformation field, while the model is no need to be scaled up. The loading conditions and boundary conditions are more in line with the actual situation of the project. With the great progress made in the construction of large-scale geotechnical experimental platforms in China, Beijing University of Technology has built the largest underground engineering comprehensive test platform (6 m × 6 m × 10 m) in China and has reached the world's advanced level. Large-scale testing is suitable for conducting multi-field and multi-state simulation demonstration studies of important projects.

The model test is still the most intuitive method for the research on deformation related to underground excavation. A reasonable test plan must be selected according to the research objectives and content. Distortion of small-scale test results is more serious because of the scale effect on the stress field or deformation field; however, large-scale testing is too expensive and time consuming. Centrifuge test pit excavation simulation experience is still lacking, so more study on simulation methods, such as excavation under unloading conditions is needed.

3 Research on environmental protection measures

Underground space development inevitably has an impact on the surrounding environment. When the impact exceeds the existing building construction allowable deformation value, corresponding engineering measures need to be taken to control the deformation of the building. According to different protection objectives, control measures can be divided into active reinforcement technologies to reduce the impact sources and passive reinforcement technologies to protect affected structures.

3.1 Active reinforcement technologies

Active reinforcement technologies mostly aim to control deformation by adjusting the construction technology and construction process during foundation pit excavation or tunnel excavation. Among them, non-excavation techniques, such as the shield method and the top tube method, have good systematic construction. Generally, adjustment of construction parameters, such as the propulsion speed and cutter head pressure, is used to control the deformation of the surrounding environment. The area of the surrounding soil that is excavated is supplemented by the secondary grouting method in the area of sensitive deformation. Due to the large-scale excavation of foundation pits, the excavation and unloading cause a wide range of influence on the deformation of surrounding environment, and various active reinforcement technologies are required to reinforce the foundation pit itself. The commonly used active environmental control technologies for foundation pits include reinforcing the soil of the foundation pit, optimizing the containment system of the foundation pit, cutting off the groundwater precipitation and recharging technology, and so on.

Soil reinforcement of the foundation pit involves the use of ground improvement methods for reinforcing the soil of the pit bottom and thus increasing the resistance of the passive zone. The high-pressure jet grouting method, full-section grouting method, and cement-soil mixing piles are used to improve the strength and properties of soil in the excavation-affected zone, to provide support for the containment structure, and to control the development of the main deformation zone of the foundation pit.

Large-scale precipitation around the foundation pit will cause large-area settlement in the surrounding area. It is necessary to adopt groundwater isolation or recharging techniques to control the area affected by precipitation. Yu et al. [8] proposed a design method and procedure for a recharging system. This system can recharge extracted groundwater to the ground to reduce the drop of the groundwater level so as to avoid settlement caused by consolidation of the ground.

3.2 Passive reinforcement technology

The passive reinforcement technology is applied to reinforce the affected structures to ensure that the surrounding construction will not produce obvious cracking damage during the excavation of underground space. The common passive reinforcement technologies include partition methods, foundation underpinning techniques, and grouting reinforcement techniques.

The partition method blocks changes in the stress field due to the excavation of foundation pit by setting up isolation piles between the foundation pit and the protected building. The partition method often uses steel sheet piles, root piles, deep mixing piles, etc. to form a wall with a certain rigidity to withstand the lateral forces and frictional resistance caused by the excavation of the foundation pit.

To control the foundation settlement of the immersed tunnel in the submarine of the Hong Kong–Zhuhai–Macao Bridge, four sets of indoor model tests regarding isolation pile bearing under a high side load were performed [9] to verify the effect of the isolated pile partitioning on the deformation field. The isolation pile is passively stressed under a side load. The maximum axial force of the pile adjacent to the isolation pile was reduced by about 10% in comparison with the pile without the isolation pile, and the maximum bending moment of the pile was reduced by about 20%. It can be seen that isolation effect of the isolated pile is significant.

The foundation underpinning technique gradually transfers the load of the existing building to the new underpinning foundation to avoid excessive differential settlement caused by the existing building foundation under changes in the ground stress field.

The grouting reinforcement technology is the grouting reinforcement of the soil surrounding an existing building to improve the bearing capacity and modulus of the soil. It is most suitable for strengthening an independent foundation or a strip foundation construction. The commonly used grouting methods are compaction grouting and split grouting. The mechanism of grouting reinforcement effect has been deeply studied and recognized, but there still have been few relevant papers published on the method of grouting and the control of grouting pressure in the practice of reinforcement of existing buildings.

4 Trends and suggestions

The main challenge in underground space development in China has gradually shifted from the stability problem of early subterranean works to control of deformation in the surrounding environment in underground engineering. The prediction and control technology of environmental deformation in underground space development will become increasingly important.

The monitoring of deformation and settlement of the entire life cycle of important buildings and structures has become possible with the rapid development of the Internet of Things technology, which helps to infer the allowable deformation values of the buildings and provide corresponding deformation control standards.

The monitoring data of foundation pit deformation stored in the cloud terminal combined with big data analysis technology can better analyze the deformation characteristics of the same type of foundation pit, and make the fitting data of various empirical formulas expand rapidly.

We should follow the example of Europe and the United States to vigorously promote the transformation of existing research results into engineering practice guidelines, and we should continue to collect and improve environmental control cases to complement each region. Because the territory of China is vast, different areas should set different building protection standards according to their own experience and conditions.

The existing analysis calculation theory of environmental impact should be further improved, and an environmental analysis method that considers the influence of a variety of factors, such as the differences between hydrogeological conditions in different regions, the complex properties of geotechnical materials, the surrounding environment, and the differences of load, should be established. We will vigorously develop numerical analysis methods and combine local underground engineering development experiences to compile numerical simulation manuals.

As underground space construction gradually develops into deep underground space and China's inland areas, it is necessary to keep abreast of the existing engineering practices, and carry out model tests and numerical simulations for special geological conditions, underground space layout, structural forms, and construction methods. It aims to solve the environmental problems caused by excavation in under-consolidated soil areas, stability of subsurface excavation methods in soft soil areas, settlement control problems, deformation control problems in the development of super-close underground space, excavation of ultra-deep foundation pits, precipitation and recharge, and so forth.

5 Conclusions

It is becoming more and more important to predict and control the deformation of underground excavation in cities.

Through theoretical derivation, model tests, statistical analysis of field measurements, and other methods, we studied the impact on the environment surrounding a deformation field caused by the excavation of foundation pits, and we established a preliminary understanding of the deformation behavior of underground excavation.

Deformation control technology is still in the implementation stage of experience guidance, and it is necessary to further clarify the principle of deformation control.

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