Analysis of Deformation of Ground and Connected Aisle with the Influence of Sump-Pit Excavation in the Aisle

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Abstract. The excavation of connected aisle is one of the key risks for the construction of subway in the coastal soft clay layer. The excavation of sump-pit will adversely affect the deformation of the ground and connected aisle, increase the risk of the project. The finite element software ABAQUS is used to carry out numerical simulation research on the excavation of sump-pit. The influence of deformation of ground and connected aisle were analyzed by the method of changing the position of sump-pit excavation. The result showed that: the most significant influence of sump-pit excavation was crown settlement, the second important influence was ground settlement, and the influence of headroom convergence was slight. The maximum ground settlement increased by 7% and the maximum crown settlement by 13% if the sump-pit was built in the middle of connected aisle.

1. Introduction
In the coastal soft clay layer, there will inevitably be a certain degree of leakage in the subway tunnel because of the abundant groundwater. Therefore, a sump-pit must be set at the lower part of the tunnel to collect and discharge the leakage water from the tunnel structure, as well as the flushing and fire fighting waste water. The sump-pit is usually set in the connected aisle of the subway tunnel, which makes the connected aisle concurrently act as the evacuation aisle and the pump room.

Because the design of sump-pit is conservative nowadays, the effective volume of sump-pit is large. If the influence of excavation of sump-pit is neglected in the design and construction process, the project risk will be greatly increased. At present, the research on the secondary excavation of underground structures mostly focuses on the foundation pit project with inner pit. Many and some other scholars have carried out numerical simulation research on the influence of excavation of inner pit on the deformation of surrounding structure and soil [1-3]. Caiwei [4] analyzed the monitoring data of deformation of ground and connected aisle caused by the excavation of sump-pit, and put forward the deformation control scheme. Yang Zhuangzhi [5] summarized the experience of design and construction of sump-pit in Beijing, and put forward some optimization suggestions.

At present, few papers have systematically analyzed the deformation of the ground and connected aisle caused by the excavation of sump-pit. In this paper, the ABAQUS finite element software is used to simulate the excavation of sump-pit in Fuzhou Subway Line 2. The influence of the excavation of sump-pit on ground settlement, crown settlement and headroom convergence is systematically analyzed, which provides a useful reference for similar projects.
2. Project background

2.1. Project introduce
A connected aisle of Fuzhou Subway Line 2 is located below Fuma Road, with the center distance of YDK35+898.179 (ZDK35+939.022). Above the left line is the Fuzhou Shuntai Motor Vehicle Inspection Company, above the right line is the Fuzhou West Third Ring Road. The connected aisle is a straight wall arch tunnel of 40.2 m (length) × 3.76 m (width) × 4.04 m (height). There are 2 sump-pit set at the left and right ends of the connected aisle, the dimension is 5.56 m (length) × 3.76 m (width) × 3.82 m (height). Both the connected aisle and the sump-pit are of composite lining structure, the primary lining is steel arch and 230 mm thick C25 shotcrete, and the secondary lining is 400 mm thick moulded concrete. The sections of the connected aisle and the sump-pit are shown in Fig. 1 and 2.

![Figure 1. Cross section of sump-pit](image1)

![Figure 2. Vertical section of sump-pit](image2)

Due to the large dimension of the connected aisle and the strict control of the ground deformation, the two-way freezing method is used to reinforce the soil to be excavated. The connected aisle is excavated by mine method. The sump-pit is excavated after the connected aisle is completely excavated and supported.

2.2. Geology and hydrological conditions
The connected aisle is buried at 20 m. The distribution of stratum from top to bottom is: thin layer sand <3-5>, (mud) medium sand <3-3>, clay <3-1>, strong weathered granite <7-1>. The position of the connected aisle is: silt soil with thin layer sand <3-5>, (mud) medium sand <3-3>, clay <3-1>. Groundwater includes upper layer stagnant water and confined water according to burial conditions. The confined water can be divided into loose rock pore confined water and bedrock pore-fracture confined water according to the medium. The geological section is shown in Fig. 3.

3. Finite element model
ABAQUS finite element software is used to analyze the elastic-plastic characteristics of the excavation of sump-pit. The three-dimensional finite element model is shown in Fig. 4. In order to reduce the influence of the boundary effect, the z direction of the model is taken as the tunnel excavation length of 40 m, and the x direction extends from the tunnel center line to the left and right sides by 25 m (50 m in total), and the y direction is up to the surface and down to 30 m below the tunnel center line (50 m in total). The normal displacement of the four sides of the model and the normal and tangential displacement of the bottom are constrained.

The D-P model is used to simulate the soil element. For the convenience of analysis, the soil layers with similar mechanical properties are simplified. The soil within 2 m around the tunnel is set as artificial frozen soil. Linear elastic model is used to simulate tunnel support structure, the primary lining and secondary lining are all simulated by solid elements. The mechanical parameters of soil and supporting structure are shown in Table 1.
Table 1. Mechanical parameters of soil and supporting structure

| Item                     | Bulk density $(\text{kN} \cdot \text{m}^{-3})$ | Yong's modulus (MPa) | Poisson's ratio | Cohesive force (kPa) | Internal friction angle ($^\circ$) |
|--------------------------|----------------------------------------------|----------------------|-----------------|-----------------------|----------------------------------|
| Miscellaneous fill       | 18.5                                         | 18                   | 0.35            | 16                    | 18                               |
| Silt                     | 16                                           | 9.4                  | 10.38           | 10.4                  | 5.5                              |
| Silt soil with thin sand | 17.1                                         | 25                   | 0.39            | 19.7                  | 15.5                             |
| Medium sand              | 19                                           | 40                   | 0.33            | 3                     | 32                               |
| Fully weathered granite  | 21                                           | 180                  | 0.23            | 20                    | 120                              |
| Frozen soil              | 19                                           | 1100                 | 0.33            | 3                     | 132                              |
| Primary lining           | 25                                           | 2800                 | 0.2             | –                     | –                                |
| Secondary lining         | 30                                           | 3150                 | 0.2             | –                     | –                                |

4. Influence of sump excavation on deformation of ground and connected aisle

Since sump-pit excavation is carried out after the completion of the connected aisle excavation, the stress release of the surrounding soil during the excavation process will aggravate the deformation of connected aisle and the ground above it. If effective control measures are not taken, the safety of project and surrounding buildings will be adversely affected.

Fig. 5 and 6 show the vertical ground settlement and its increment caused by the excavation of sump-pit. It can be seen that after the completion of the excavation of connected aisle and before the excavation of sump-pit, the vertical ground settlement curve is U–shaped. It is because when the opposite excavation face is pushed from the two ends of connected aisle to the middle, the distance between the excavation faces decreases and the mutual disturbance increases, resulting in greater ground settlement above the middle section of connected aisle. With the excavation of sump-pit, the ground settlement is increasing, and the maximum ground settlement always appears above the middle of the connected aisle. However, due to the large buried depth of the connected aisle and the position of sump-pit underneath it, the excavation of sump-pit mainly causes the stress release of the soil under the connected aisle, which has little effect on the ground settlement. The maximum increment of ground settlement caused by the excavation of sump is only 14% of the maximum ground settlement before the excavation.
Figure 5. Ground settlement during the excavation of sump-pit

The vertical ground settlement incremental curve obtained by numerical simulation and field measurement are both n–shaped. The excavation of the sump-pit has a slightly greater impact on the ground settlement in a certain range above it than that in the middle of the connected aisle, which shows that the model has a high reliability for the simulation of the excavation of sump-pit.

Figure 7 and Figure 8 show the crown settlement and its increment caused by the sump excavation. It can be seen that the variation law of crown settlement caused by the excavation of sump-pit is similar to that of ground settlement, but the influence of the excavation on crown settlement is much significant than that of ground settlement. The maximum increment of crown settlement caused by the excavation is 5.94 mm, which is 49% of the maximum crown settlement before the excavation. After the excavation of sump-pit, the maximum crown settlement of the connected aisle is 16 mm, which does not reach the engineering warning value of 20 mm. However, due to the faster excavation speed and shorter construction period of sump-pit, the greater growth rate of crown settlement will greatly increase the risk of the project, which needs to be vigilant.

Figure 9 and Figure 10 show the headroom convergence and its increment caused by the sump-pit excavation. It can be seen that with the excavation of sump-pit, the headroom convergence of the connected aisle is slightly reduced from the left and right ends of the connected aisle to the midpoint of the long side of sump-pit, and slightly increased from the midpoint of the long side of sump-pit to the middle of the connected aisle. In general, the effect of sump-pit excavation on headroom convergence is slight, which has no substantial impact on the project. In the following study, the influence of the sump-pit excavation on headroom convergence will be neglected.
5. Influence of sump position on deformation of ground and connected aisle

The sump-pit is usually located in the middle of the connected aisle. Because of the large length of the connected aisle and the use of freezing method, in order to make the installation of the freezing pipe easier, the collection and drainage efficiency of the sump-pit is higher, the sump-pit is located at both ends of the connected aisle. Based on the background of this project, analyzing the influence of the position of sump-pit on the deformation of the ground and connected aisle by comparing two working conditions of the sump-pit located at both ends of the connected aisle (working condition 1) and the sump-pit located in the middle of the connected aisle (working condition 2). The excavation dimension of the central sump-pit is 7 m (length) × 3.8 m (width) × 5.4 m (height).

Fig. 11 and 12 are the vertical ground settlement and its increment under working conditions 1 and 2. It can be seen that: (1) Different from working condition 1, the ground settlement of working condition 2 is larger in the range of 6-34 m from the left line tunnel, and smaller in the range of 0-6 m and 34-40 m from the left line tunnel. (2) The maximum ground settlement and its increment of working condition 2 are larger than those of working condition 1, and the differential settlement is more significant. The maximum ground settlement of working condition 2 increased by 7% compared with working condition 1, reaching 24.6 mm, which exceeded the engineering warning value. It is because the single sump dimension in working condition 2 is larger than that in working condition 1, so the excavation of sump-pit will cause greater disturbance to the soil.

Fig. 13 and 14 are the crown settlement and its increment under working conditions 1 and 2. It can be seen that, the influence law of the central sump-pit excavation on the crown settlement is similar to that of the vertical ground settlement, but the degree of influence is more significant. Different from working condition 1, the crown settlement of the working condition 2 is larger in the range of 4-36 m from the left line tunnel, and slightly smaller in the range of 0-4 m and 36-40 m from the left line tunnel.
tunnel. The maximum crown settlement of working condition 2 increased by 13% compared with working condition 1, reaching 21.15 mm, which exceeded the engineering warning value.

Figure 13. Crown settlement of conditions 1 and 2

Figure 14. Crown settlement increment of conditions 1 and 2

6. Conclusion
(1) The excavation of sump-pit will aggravate the ground and crown settlement and the headroom convergence of the connected aisle, increasing the project risk. The freezing method is used to reinforce the soil in this project, because of the good supporting effect of the freezing wall, none of the three indexes reach the engineering warning value.

(2) The excavation of sump-pit has the most significant effect on the crown settlement, which can increase the maximum crown settlement by 49%; the effect on ground settlement is smaller, which can increase the maximum ground settlement by 14%; and the effect on headroom convergence is very slight, which can be neglected in engineering.

(3) Locating the sump-pit in the middle of the connected aisle will increase the maximum ground settlement by 7% and the maximum crown settlement by 13%, which all exceed the engineering warning value. Therefore, it is more reasonable to locate the sump-pit at both ends of the connected aisle.

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