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Study on the Reasonable Overlying Strata Thickness for Metro Tunnel through the Raft Foundation Buildings in Upper-soft and Lower-hard Strata

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Abstract. This paper was based on the engineering practice of Qingdao metro tunnel through a raft foundation. The methods of numerical calculation and inversion analysis of field monitoring data were used to analyze the reasonable overlying strata thickness for metro tunnel through the raft foundation buildings in upper-soft and lower-hard strata. The concept of reasonable overlying strata thickness was proposed based on full utilizing the self-stability of surrounding rock when the metro tunnels through the raft foundation. It was pointed out that the self-stability of surrounding rock increased rapidly with the increase of overlying strata thickness firstly, and tended to stabilize when the overlying strata thickness reached a certain value; and then the influence of the overlying strata thickness on self-stability was not obvious thereafter. The reasonable overlying strata thickness for the metro tunnels through the raft foundation was about 5.0 ~ 6.0 m in the upper-soft and lower-hard strata in Qingdao. The research conclusion had certain reference value for the design and construction of the metro tunnels through the raft foundation safely, economically and quickly.

1. Introduction

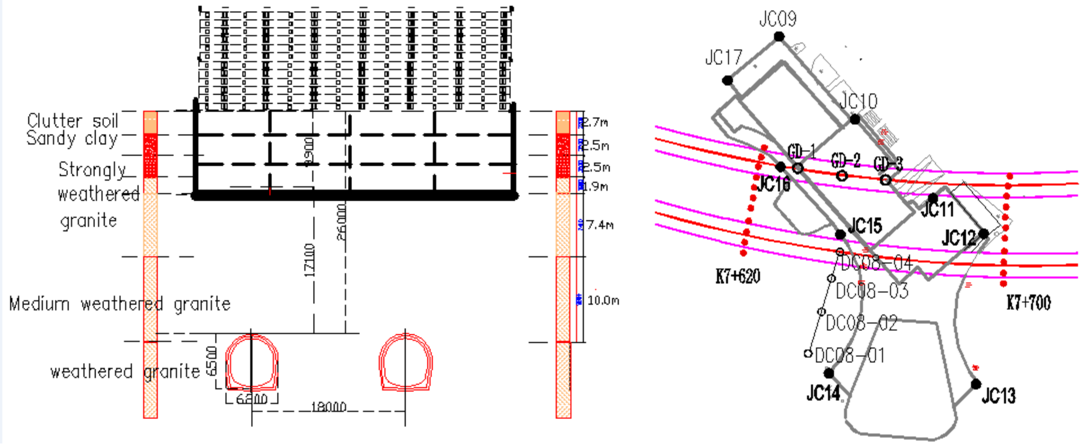
The fundamental purpose of the excellent metro tunnel engineering design is to fully utilize the self-stability of surrounding rock, and minimize the use of auxiliary measures, and emphasize the economy on the basis of safety. If the metro tunnel is built in the hard surrounding rock, the surrounding rock can be stabilized itself. The metro is usually built in a large urban area with many buildings, large population density and heavy traffic. Due to the technical standard of line radius and other related technical standards, it often needs to pass through a large number of existing buildings. In the face of the problem, It is important to built the tunnel in a reasonable thickness of rock, which can utilize the self-stability of the surrounding rock, reduce the risk and difficulty of construction, select the excavation method flexibly, reduce the supporting measures, save the construction cost, reduce the influence on the surrounding environment and so on[1~5]. ZAHNG et al. and other scholars[6~8] made a deep discussion on the interaction between the underground cavern and the foundation in the stratum. However, there is no unified understanding between the academic and engineering circles at home and abroad about the reasonable thickness of the overlying strata above the tunnel vault, which is necessary for further study.

Based on the practice of metro engineering in Qingdao, this paper takes the tunnel through a raft building as the research object. Based on the basic principle of Strength Reduction Finite Element Method, this paper studies systematically the problem of the reasonable overlying thickness of metro tunnels through the raft foundation in upper-soft and lower-hard strata by using the method of numerical calculation combined with the inversion analysis of engineering measured data. The research conclusion has certain reference value for the design and construction of metro tunnel crossing underneath the raft foundation safely, economically and quickly.

2. Engineering Survey

Qingdao is located in the southwest of the Jiaodong Peninsula , bordering on Yellow Sea. And it is located in the late stage of the deep formed granite rock base in the Yanshan, and is intruded by some rocks such as the porphyry and granite porphyry. During the long geological history period, a certain thickness of the weathering zone has been formed under the combined force of internal and external forces, and the Quaternary loose accumulative layers have been deposited on it. The vertical distribution of geological bodies is uneven, the distribution of strata changes frequently and the thickness of strata changes greatly, and the stratigraphic interface fluctuates greatly, which has obvious distribution characteristics of upper-soft and lower-hard strata.

The Qingdao Metro Line M3 is 24.78 km long and runs through 93 buildings, including 11 high-rise raft foundation buildings[10].The K7+620.0 ~ K7+700.0 mileage section of the metro line is double-line and double-tunnel. The distance of middle line between the left and right tunnels is about 18.0 m. The size of the excavation section is 6.2 m x 6.5 m, which is excavated by benching method of mining method, and composite lining is used. The tunnel passes underneath a raft building at an angle of about 45° within this mileage. The distribution and thickness of the strata in this area are about 2.7 m for the clutter soil and 2.5 m for the sandy clay of Quaternary strata , 2.5 m for the upper subzone of strongly weathered granite, 1.9 m for the central zone and 7.4 m for the lower subzone. The thickness of mediurn weathered granite strata is about 10.0 m, and below it is weathered granite strata. The building, which was built in 2000, is about 66.0m long and 15.2m wide. The main building is a tube frame structure with 15 floors on the ground and 2 stories underground. There are 3 floors on the ground and 1 floor underground of the podium building. The building uses the raft foundation with a depth of 9.9 m. The vertical distance between the vault of the tunnel and the base of the building is from 15.0m to 17.0m, in which the thickness of the medium weathered granite rock is 8.0m to 10.0m, as shown in Figure 1.



（a）Cross section diagram （b）Plan

Figure 1. Section and plan of metro tunnel through the raft foundation building

3. Study on reasonable overlying strata thickness of metro tunnels under raft foundation buildings in upper-soft and lower-hard strata

3.1Research methods and calculation parameters

3.1.1 Research methods

Strength Reduction Finite Element Method obtains the safety coefficient of surrounding rock by continuously reducing the strength parameters of rock and soil around the tunnel cavern until it is in the state of ultimate stability. It has strict mechanical basis, can reflect reality, and has the advantages of visual, dynamic and quantitative calculation [10~13]. It is widely used in the stability analysis of surrounding rock of tunnel through buildings [6~8].

Displacement is the most direct reflection of the stability of the surrounding rock. When the surrounding rock is in the elastic state, the displacement around the tunnel caused by tunnel excavation is small. When the surrounding rock is in the plastic state, the displacement around the tunnel is increased rapidly, which results in material damage. When the plasticity of the surrounding rock develops to a certain extent, there will be local cracks at the stress concentration. With the further development of the plastic state, the displacement around the tunnel increases infinitely, the local cracks penetrate, and the fracture surface is formed, and the surrounding rock is destabilized. Therefore, the displacement sequence of the surrounding characteristic points of the tunnel can be regarded as the evaluation index of the stability of the surrounding rock.

In order to calculate the safety factor of surrounding rock stability of metro tunnel through the raft foundation, the stress and deformation state of initial model tunnel excavation is calculated first, then the strength parameters c and φ of rock and soil are reduced according to formula (1). Then the reduced strength parameters are input into the initial model for excavation calculation. In the calculation process, the displacement of the arch roof of the surrounding rock of the tunnel is recorded. When the displacement changes suddenly, the corresponding reduction coefficient is the safety factor of the surrounding rock of the tunnel.

$$c' = \frac{c}{\omega} \quad \varphi' = arc\left(\frac{\tan\varphi}{\omega}\right) \qquad (1)$$

In the formula, ω is the reduction factor.

3.1.2 Calculation parameters

According to the statistical analysis results of physical and mechanical parameters of rock and soil along Qingdao Metro with reference to the current standards and related research results [14]~[15], the physical and mechanical parameters of rock and soil and the thickness of various strata are shown in Table 1.

Table 1. Physical and mechanical parameters of the rock and soil mass

Layer Type	Elastic Modulus	Poisson Ratio	Weight	Cohesion	Internal Friction Angle	Thickness
Quaternary soil	0.04Gpa	0.38	17.5 KN/m3	0.025Mpa	20°	5.2m
Strongly weathered granite	0.05Gpa	0.28	22.5 KN/m3	0.042Mpa	31°	11.8m
Medium weathered granite	5.0Gpa	0.25	24.5 KN/m3	0.60Mpa	35°	10.0m
Weathered granite	22.0Gpa	0.22	26.0 KN/m3	1.60Mpa	43°	∞

3.2 Calculation model and results

3.2.1 Calculation model

The vertical displacement of the vault of the tunnel through the raft foundation is calculated by using the three-dimensional finite element model which takes the length of 100m in Z axis direction along the tunnel, the length of 60m in the X axis direction in the horizontal plane and the length of 86m in the Y axis direction. The bottom of the model is fixed, the left and right sides apply horizontal

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displacement constraints, and the upper boundary is taken to the surface. The eight node quadrilateral isoparametric element is used to model the tunnel and the surrounding of the foundation is encrypted and the left and right lines are staggered at 16m and the full section is excavated synchronously with 2.0 m per cycle. The DP3 yield criterion[11] is adopted in the calculation. The rock and soil are considered as the ideal elastoplastic body, and the surface and strata are all horizontally distributed. The initial stress only considers the weight of rock and soil. The building load is converted to the equivalent uniform load acting on the foundation surface vertically [1]~[5].Each layer of the ground is considered by 15kpa and each layer of the basement is considered by 20KPa. The initial stress is 265kpa in total, which the support measures, blasting vibration and other construction factors are not considered. The calculation model is shown in Figure 2. The results of three-dimensional numerical calculation show that the vertical displacement of the tunnel vault caused by the excavation of the tunnel under the high-rise raft foundation is 0.698 mm.

In view of the large number of three-dimensional calculation units and large amount of calculation, two-dimensional finite element plane numerical calculation model is adopted in the following steps, which only considers the single tunnel factor, the tunnel direction is vertically to the basic direction and the DP4 yield criterion [16] is adopted and the stress release ratio of the tunnel full section excavation is 100% at a time. The results of two-dimensional plane numerical calculation show that the vertical displacement of the tunnel vault caused by the tunnel excavation under the high-rise raft foundation of the metro tunnel is 0.791mm and the relative error of the three-dimensional calculation results is about 11.6%. Therefore the calculation conclusion is reliable.

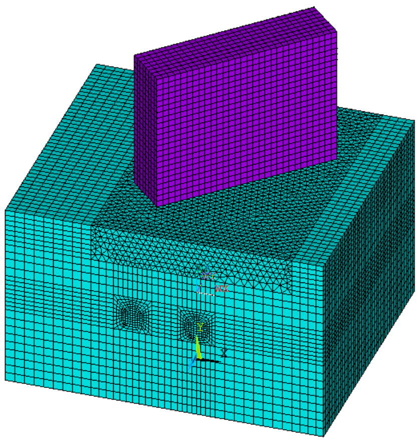


Figure 2. Finite element numerical calculation model

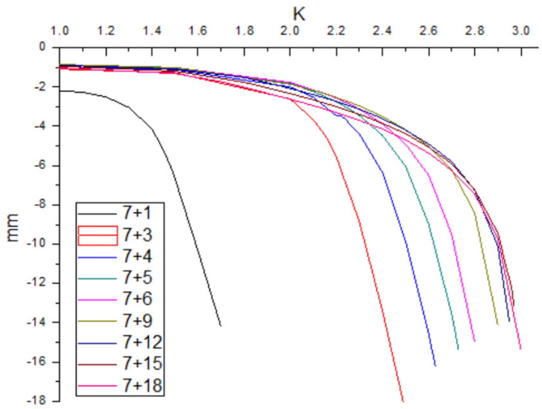


Figure 3. Vertical displacements of tunnel vault

3.2.2 Calculation results

In order to systematically study the reasonable overlying thickness of the tunnel through the raft foundation building of Qingdao Metro, the thickness is determined to be a total of 10 construction conditions of 0.8m~18m.The variation curve of vertical displacement with the strength of surrounding rock under different working conditions are shown in Figure 3. The calculated results of safety factor are given in Table 2 and Figure 4.

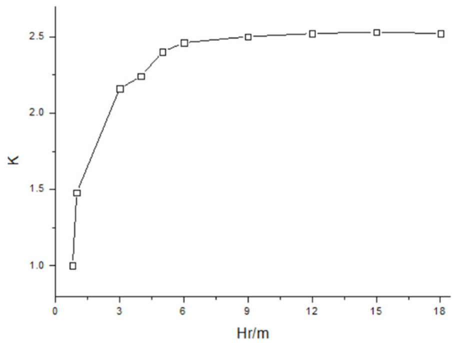


Figure 4. Safety factor varying with overlying strata thickness

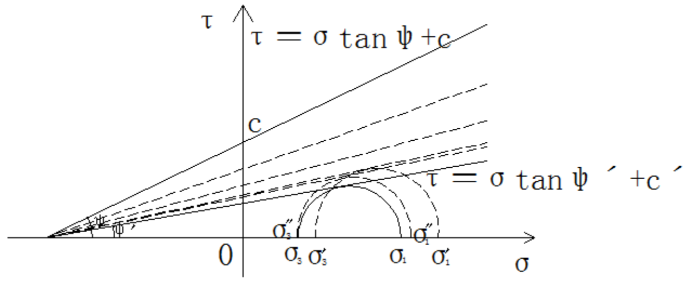


Figure 5. The sketch map of safety factor in different stress path

Table 2. Calculation result of safety factor

Thickness（m）	0.8	1	3	4	5	6	9	12	15	18
Safety Factor	1.00	1. 32	2.16	2.24	2.40	2.46	2.50	2.52	2.53	2.52

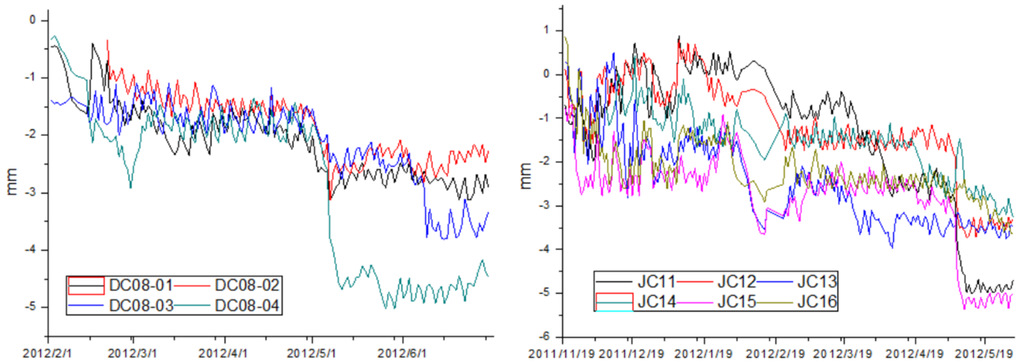
It can be seen that the safety factor increases rapidly from 1.00 to 1.32 ~ 2.16 and 2.24 when the overlying thickness increases from 0.8 m to 1 m ~ 3 m and 4 m; When the overburden thickness increases from 5m to 6m, the safety factor increases from 2.40 to 2.46, and the rate of increase was significantly reduced. Then, the thickness of overlying strata continues to increase, and the safety factor tends to be stable. This is because the strength reduction method is essentially the limit state method. The additional stress produced by the building load decreases with the thickness of the overlying strata increases. The gravity stress of surrounding rock increases with the increase of overlying thickness[6].The variation of surrounding rock stress with the overlying strata thickness must have a process from large to small. The smaller the surrounding rock stress is, the closer the circle is to the origin of coordinates, the smaller the radius is, and the larger the corresponding safety factor is[18].Therefore, the safety factor increases with the increase of overlying strata thickness. Because of the limited influence range of the additional stress on the basement, the influence of building load can be neglected after the overlying thickness reaches a certain value. And the stress of surrounding rock around the tunnel is gradually reduced by the weight of overburden rock and soil mass, so the safety factor tends to be stable when the overburden thickness reaches a certain value, as shown in Figure 5.

3.3 Discussion on reasonable overlying strata thickness of metro tunnels crossing high rise raft foundation

The self-stabilization ability of surrounding rock increases rapidly with the increase of overlying strata thickness firstly, when the metro tunnel through the raft foundation buildings in upper-soft and lower-hard strata, and tends to stabilize when the overlying strata thickness reached a certain value. Then the effect of increasing the overlying thickness on the self stabilizing ability of surrounding rock is not obvious. Based on fully utilizing the self-stability ability of surrounding rock, and taking into account various factors such as safety, economy and function of metro tunnel, the reasonable overlying strata thickness should be defined as the smallest overlying thickness when the stability of the surrounding rock tends to be stable with the increases of the overlying strata thickness. The reasonable overlying strata thickness is about 5.0 ~ 6.0 m when the metro tunnels through the raft foundation in the upper-soft and lower-hard strata in Qingdao.

4.Field monitoring data analysis

During the excavation of the metro tunnel through the raft foundation under the K7+620.0 ~ K7+700.0 mileage of the Qingdao Metro, the whole process of the settlement of the ground surface and the buildings is monitored. The surface and building monitoring points are arranged as shown in Fig. 1b, and the time history curve of settlement monitoring data is shown in Figure 6.



(a) Surface settlement （b）Building settlement

Figure 6. Time-history curves of surface and building settlement

As shown in Figure 6, because of the ground surface settlement monitoring points are set on the right side of the line, and the ground settlement data is small when the left line of the tunnel is excavated about February 1, 2012. On May 7, 2012, the ground settlement caused by the excavation of the right line increased greatly, and the maximum value of the ground settlement was 4.86 mm. Since then, the monitoring data tended to be stable. The time history curve of building settlement shows a similar law, and the maximum value of building settlement is 5.25mm.It shows that when the overlying thickness is 5.0~6.0m, the excavation of metro tunnel through the high-rise raft foundation building has little influence on the surface and buildings, which verifies the rationality of the conclusion obtained in this paper.

5. Conclusions

(1) The self-stabilization ability of surrounding rock increases rapidly with the increase of overlying strata thickness firstly, when the metro tunnel through the raft foundation buildings in upper-soft and lower-hard strata, and tends to stabilize when the overlying strata thickness reached a certain value. Then the effect of increasing the overlying thickness on the self stabilizing ability of surrounding rock is not obvious.

(2) The concept of reasonable overlying strata thickness is proposed based on full utilizing the self-stability of surrounding rock when the metro tunnels through the raft foundation. And it is pointed out that the reasonable overlying strata thickness should be defined as the smallest overlying thickness when the stability of the surrounding rock tends to be stable with the increases of the overlying strata thickness.

(3) The reasonable overlying strata thickness is about 5.0 ~ 6.0 m when the metro tunnels through the raft foundation in the upper-soft and lower-hard strata in Qingdao.

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