Research on the Opportunity of Construction Method Conversion in Upper-Soft and Lower-Hard Stratum Based on Pressure Arch Theory

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Abstract. In order to determine the construction method conversion opportunity from Cross Diaphragm with Step method to three-bench method of Zi-Zhi Tunnel, this paper takes the shallow buried excavation section of the tunnel as an example, where the stratum is upper-soft and lower-hard. Considering different intersection positions between tunnel face and the interface of stratum, based on the pressure arch theory, the change laws for the pressure arch thickness under different conditions were analyzed by FLAC^{3D}. Then, a construction method conversion opportunity is derived. Meanwhile, the rationality of conversion opportunity is validated by the field monitoring. The results indicate that: the pressure arch thickness reaches a stable state and self-stable ability of surrounding rock reaches its maximum when the distance between tunnel bottom and the interface of strata is greater than 13 m. Hence, it is suggested to convert the construction method when the distance is greater than 13 m; the stable value and the convergence rate of vault subsidence are both below warning value in site, which can meet the safety and economic benefits of engineering.

Keywords: Pressure arch · Upper-soft and lower-hard · Construction method conversion

1 Introduction

Tunnel construction is mostly conducted in a single stratum. However, when tunnel passes through upper-soft and lower-hard formation, single excavation method could not meet the requirements of safe and schedule. In this case, excavation method should be adjusted dynamically according to the geological condition. Reasonable construction method conversion opportunity could reduce the disturbance of surrounding rock. Therefore, it is of significant value to study on the construction method conversion opportunity in upper-soft and lower-hard stratum.

Currently, the study on tunnel construction in upper-soft and lower-hard formation focused more on excavation methods comparisons (Diao and Li 2007; Zhang et al. 2011)

S. Agaiby and P. Grasso (eds.), *Engineering Challenges for Sustainable Underground Use*,
Sustainable Civil Infrastructures, DOI 10.1007/978-3-319-61636-0_2

and safety research (Liu et al. 2014), while less on the influence of conversion opportunity on surrounding rock stability. Moreover, in construction practices, the conversion opportunity is mostly based on engineering experiences, though calculation method of relaxation pressure of shallow large span tunnel in up-soft and low-hard stratum has been obtained (Wang et al. 2014).

In order to determine the construction method conversion opportunity from Cross Diaphragm with Step method to three-bench method of Zi-Zhi Tunnel, based on the upper-soft and lower-hard stratum characteristic and the pressure arch theory, this paper reveals the change laws of the pressure arch thickness in different intersection positions between tunnel bottom and the interface of upper-soft and lower-hard. Engineering practice has verified the rationality of the opportunity. The results can provide references for future similar projects.

1.1 Engineering Survey

The length of Zi-Zhi Tunnel is 14.4 km. It is the longest urban tunnel of Asia. The project is divided into three sections: U-shape section, open cut section and shallow buried excavation section. This paper focuses on the shallow buried excavation section whose length, height and width is 877.1 m, 9.7 m and 12.8 m, respectively. The stratum is upper-soft and lower-hard, and the longitudinal profile is shown in Fig. 1. Design excavation methods of this shallow buried excavation section are Cross Diaphragm with Step method and three-bench method. Corresponding mileages of the two methods are shown in Fig. 1.

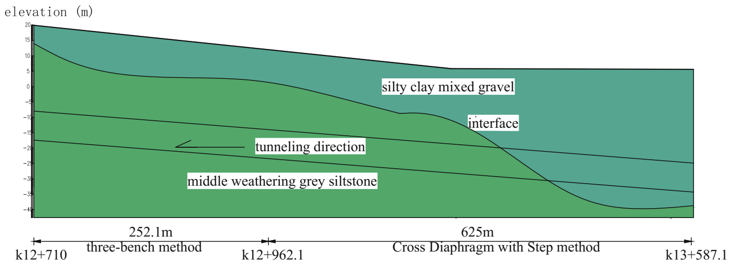

Fig. 1. The longitudinal profile of geology

With tunnel face moving forward, middle weathering grey siltstone (hereinafter referred to as the “bedrock”) gets into the tunnel face and the invading bedrock depth of tunnel bottom is increasing. The excavation sequences and designed support parameters of Cross Diaphragm with Step method are shown in Fig. 2 and Table 1, respectively. In Cross Diaphragm with Step method, working face is divided into several smaller parts, which leads to repeated rock disturbances. In addition, the working space is so limited that only artificial and light equipments can be adopted. It is difficult to

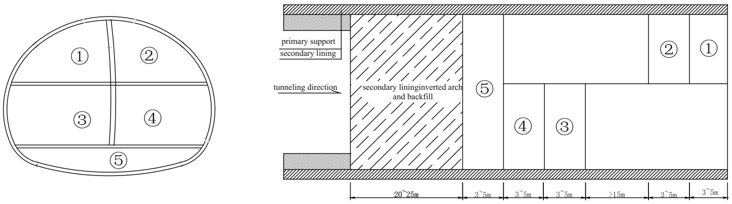

Fig. 2. Excavation sequences of Cross Diaphragm with Step method

Table 1. Support types and parameters of Cross Diaphragm with Step method

Support types	Support parameters
Primary support	C25 thick: 30 cm; I22 steel arch space: 50 cm
Secondary lining	C35 thick: 60 cm

ensure the progress of the project. To reduce the rock disturbance and ensure the construction period, construction method conversion from Cross Diaphragm with Step method to three-bench method should be conducted ahead of schedule.

1.2 Approach of Method Conversion Opportunity

1.2.1 Pressure Arch Theory

With the excavation of tunnel, initial stress field of surrounding rock is broken. And a free surface will apparent in tunnel face. Stress redistribution is produced to resist surrounding rock deformation. This phenomenon is the pressure arch effect (Lunardi 2000). According to the characteristics of surrounding rock stress distribution, surrounding rock can be divided into three cases: stress release area, stress concentration area and the original stress area, shown in Fig. 3. Stress concentration area is the main bearing unit of the surrounding rock, and the inner and outer boundary of pressure arch can be determined based on the range of the stress concentration area.

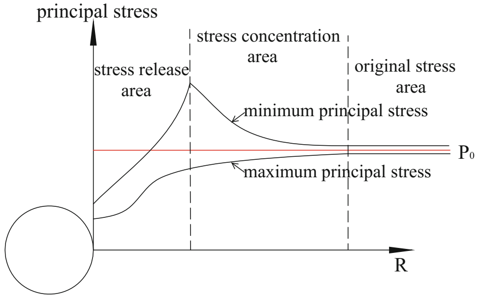

Fig. 3. Stress distribution of surrounding rock

(1) Determining method of internal boundary

The internal boundary of the pressure arch lies in tunnel perimeter if there is no horizontal stress decreasing area. Otherwise, the internal boundary lies in horizontal stress invariant points.

(2) Determining method of external boundary

Above the crown, the distribution of minimum principal stress is horizontal within pressure arch and it becomes vertical beyond pressure arch. Therefore, the direction changing point of minimum principal stress is taken as external boundary of pressure arch.

1.2.2 Calculation Model and Condition Design

Based on the geology condition, the stratum can be simplified, shown in Fig. 4. According to the geological survey and geological drilling, the calculation parameters of major soil are shown in Table 2. A 3D numerical model is established by FLAC^{3D} and its horizontal length is 90 m, vertical 60 m, and the longitudinal 1 m, shown in Fig. 5. Solid element is used to simulate surrounding rock. In addition, rock and soil model adopt the Mohr-Coulomb constitutive model.

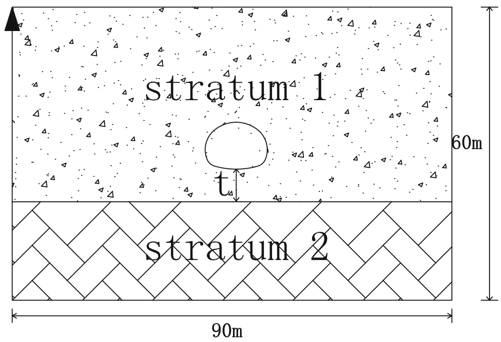

Fig. 4. Stratum simplified picture

Table 2. Calculation parameters in different stratum

Stratum	Density (kg/m^3)	Elastic modulus (GPa)	Poisson ratio	Internal friction angle (°)	Cohesion (KPa)
1	1980	0.2	0.29	17	45
2	2320	0.2	0.23	36	200

Note: 1-Silty Clay mixed Gravel, 2-Middle weathering Grey Siltstone.

In order to figure out the arching ability of surrounding rock in different intersection positions, assume that "*t*" refers to the distance between the interface of strata and tunnel bottom. "*t*" is negative when the interface is below the tunnel bottom, otherwise, "*t*" is positive. Calculation conditions are shown in Table 3.

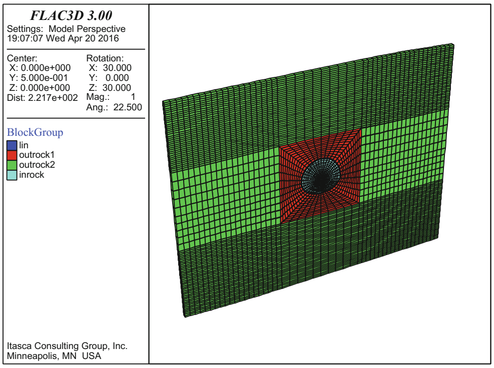

Fig. 5. Numerical calculation model

Table 3. Design of calculation conditions

Calculation conditions	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
t/m	−4	−3	−2	−1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

1.2.3 Changing Laws of Pressure Arch Thickness

In order to analyze surrounding rock stress distribution after excavation, a typical stress monitoring path is defined. The path is from crown to the upper surface of model. Horizontal stress curves in monitoring path of No. 8 calculation condition are shown in Fig. 6 and horizontal and vertical stress curves are shown in Fig. 7.

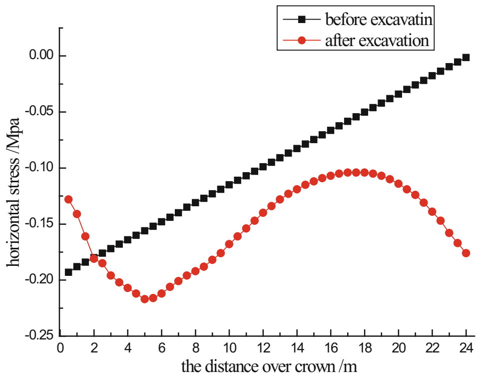

Fig. 6. Horizontal stress curve of No. 8 condition

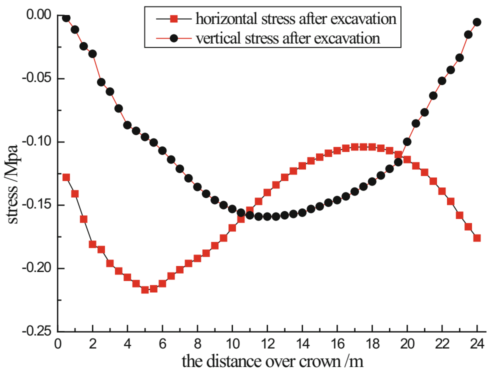

Fig. 7. Horizontal and vertical stress curves of No. 8 condition

According to the boundary determining methods of pressure arch mentioned, the intersection point of horizontal stress before and after the excavation is the internal boundary of pressure arch. And the first intersection point of horizontal and vertical stress after excavation is the external boundary. Figures 6 and 7 show that the distance between pressure arch internal boundary and crown, "a", is 2 m. And the distance between pressure arch external boundary and crown, "b", is 10.5 m. By that analogy, the statistics of pressure arch boundary about all calculation conditions are shown in Table 4 and the curve of pressure arch thickness is shown in Fig. 8.

Table 4 and Fig. 8 show that with the interface of strata increasing gradually, the changing laws of pressure arch thickness could be divided into three stages: no-arching stage, slow-decreasing stage and nearly-stable stage.

No-arching stage: when −4 m < "t" < 0 m, namely, before the bedrock invades tunnel bottom, pressure arch external boundary is confined to the ground surface, and could not form a natural pressure arch. The result indicates that stress concentration is serious and the arching ability of surrounding rock is insufficient, which is prone to cause landslides and large deformation.

Slow-decreasing stage: when 0 m < "t" < 13 m, the thickness of the pressure arch decreases quickly. The thickness of pressure arch above the vault represents the disturbance degree of surrounding rock and the self-bearing capacity. The smaller the thickness is, the less rock is required to bear load. The result indicates that with the invading bedrock depth of the tunnel bottom increasing, the arching ability of surrounding rock is improving.

Nearly-stable stage: when 13 m < "t" < 15 m, the curve is parallel to the "X" axis. The pressure arch thickness above crown tends to be stable and self-stable ability of surrounding rock reaches its maximum.

According to above analysis, it can be concluded that when the invading bedrock depth of the tunnel bottom is greater than 13 m, arching ability of surrounding rock reaches its maximum and it is conducive to utilize the self-bearing capacity of the rock mass. Therefore, it is suggested to convert the construction method after the distance between tunnel bottom and the interface of upper-soft and lower-hard stratum is greater than 13 m.

Table 4. Statistics of pressure arch boundary

t/m	a/m	b/m	The thicknesses of pressure arch/m	Produce pressure arch?
−4	2	/	∞	No
−3	2	/	∞	No
−2	2	/	∞	No
−1	2	/	∞	No
0	2	16.6	14.6	Yes
1	2	16.1	14.1	Yes
2	2	15.4	13.4	Yes
3	2	14.8	12.8	Yes
4	2	14.2	12.2	Yes
5	2	13.4	11.4	Yes
6	2	12.5	10.5	Yes
7	2	11.7	9.7	Yes
8	2	11.2	9.2	Yes
9	2	10.8	8.8	Yes
10	2	10.3	8.3	Yes
11	2	10.0	8.0	Yes
12	2	9.6	7.6	Yes
13	2	9.5	7.5	Yes
14	2	9.5	7.5	Yes
15	2	9.4	7.4	Yes

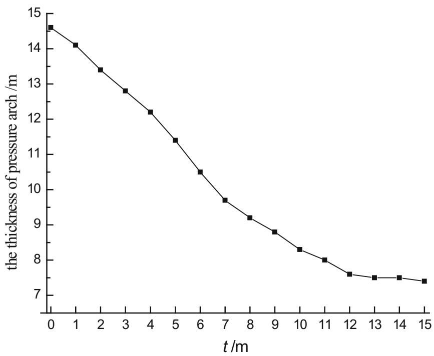

Fig. 8. Curve of pressure arch thickness under different conditions

1.3 Validation of Construction Method Conversion Opportunity

According to the construction method conversion opportunity above mentioned, the project department converted the Cross Diaphragm with Step method to three-bench method at K13 + 198.6. Excavation methods corresponding mileages in site are shown in Table 5.

Table 5. Tunnel excavation methods corresponding mileage in site

Excavation methods	Cross Diaphragm with Step method	Three-bench method
Start mileage	K13 + 587.1	K13 + 198.6
Terminal mileage	K13 + 198.6	K12 + 710
Length/m	388.5	488.6

Crown settlement and its settlement rate in K13 + 198.6 are measured. Deformation curve and deformation rate curve of crown settlement are shown in Figs. 9 and 10, respectably.

Figures 9 and 10 indicate that cumulative deformation increases rapidly and the crown settlement rate is large from an early time; After 15 days, the crown settlement rate slows down and cumulative deformation tends to be stable. The stable value of vault subsidence is 23 mm, which is lower than warning value, 30 mm. The rate of

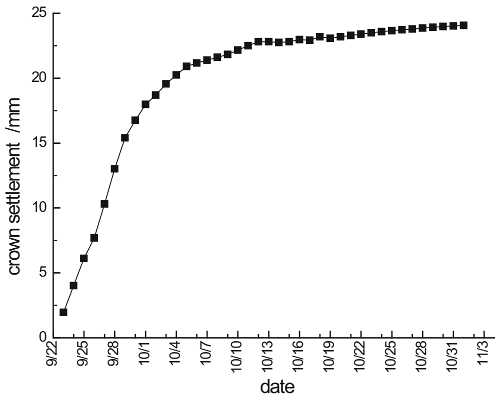

Fig. 9. Deformation curve of crown settlement

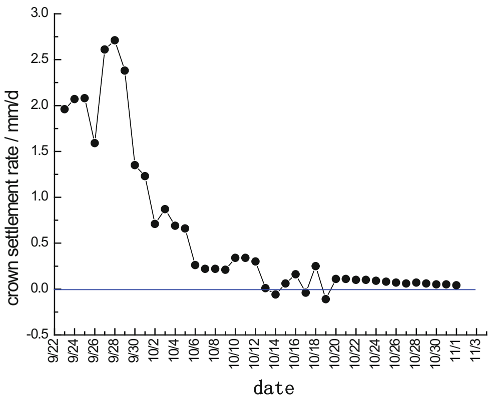

Fig. 10. Deformation rate curve of crown settlement

vault subsidence stable value is 0 mm/d, which is also lower than warning value 1 mm/d. The results show that the opportunity of construction method conversion can meet the safety benefit.

2 Conclusions

(1) In the shallow buried excavation section of Zi-Zhi Tunnel, stratum is generally upper-soft and lower-hard. To reduce the rock disturbance and ensure the construction progress, construction method conversion from Cross Diaphragm with Step method to three-bench method should be conducted ahead of schedule.
(2) According to geographical character of shallow buried excavation section of Zi-Zhi Tunnel that the invading bedrock depth of the tunnel bottom is increasing, the pressure arch thicknesses change laws under different conditions could be divided into three stages: no-arching stage, slow-decreasing stage and nearly-stable stage. Arching ability of surrounding rock reaches its maximum when the invading depth of tunnel bottom is greater than 13 m. Therefore, it is suggested to convert the construction method when the distance between tunnel bottom and the interface of strata is greater than 13 m.
(3) The stable value and its convergence rate of vault subsidence in the actual conversion mileage are both below warning value, which can meet the safe and economic benefits of engineering.

Acknowledgments. The authors appreciate the support of Science and Technology Plan Projects of Hunan Province, China (2010GK3173).

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Engineering Challenges for Sustainable Underground Use
Proceedings of the 1st GeoMEast International Congress and Exhibition, Egypt 2017 on Sustainable Civil Infrastructures
Agaiby, S.; Grasso, P. (Eds.)
2018, VIII, 233 p. 170 illus., Softcover
ISBN: 978-3-319-61635-3