Experimental study on optimization of the initial support structure of super-large section highway tunnel

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Abstract: To improve the economic benefits, on the premise of ensuring the bearing capacity of the initial support, the optimized research on the initial support structure of the super-large section highway tunnel was carried out. Based on the first single-hole four-lane highway tunnel with the largest excavation section in Shandong Province, this paper puts forward a support scheme of optimizing the arch spacing for the initial support and sets up the comparative field test to study the differences between the original scheme and the optimized scheme in bearing mechanical properties and controlling tunnel stability. The tunnel deformation characteristics, surrounding rock pressure release law and arch stress distribution rule of the two support schemes were obtained by monitoring the displacement and stress of different monitoring sections. The results show that compared with the original scheme, the clearance convergence of the optimized scheme is increased by 3.65%, the settlement increased by 5.69%, the surrounding rock pressure increased by 18.34%, and the arch stress decreased by 11.18%. In addition, the maximum stress of the arch is only 49.6% of the yield strength of steel. Both the original scheme and the optimized scheme have enough strength reserve to resist the deformation of surrounding rock and ensure the stability of the tunnel in a short time. This study can provide engineering references for constructing a super-large section highway tunnel under the same condition.

1. Introduction
In recent years, China's traffic infrastructure construction is gradually increasing, and only for highway tunnels, the average annual growth rate is more than 20%. By the end of 2018, 17738 highway tunnels and 17236.1 km in China, 1509 and 1951.0 km more than in 2017 (Ren et al., 2019; Zhao and Li, 2018; Hong, 2015). At the same time, with the rapid expansion of the city scale, frequent and intensive exchanges of people, and the rise of the logistics industry, people have an unprecedented
strong demand for transportation. Therefore, the super-large section highway tunnels with single-hole and four-lanes or more gradually come into view (Zhang et al., 2020). The most significant characteristics of super-large section highway tunnels with four lanes or more are large sections, large span, low flattening rate and complex construction technology. In the design stage, due to the lack of design standards for super-large section highway tunnels with four or more lanes, it often refers to the existing design specifications for small-span tunnels with three lanes or less, resulting in design confusion. In the construction stage, the partial excavation methods such as double-side heading method, CD method, CRD method are selected, and the dynamic construction mode of staggered excavation and support needs to be considered, which makes it difficult to determine the stress and deformation of the initial support (Wang et al., 2004; Zhou et al., 2004). Therefore, technicians are often conservative in the choice of the support structure, leading to the unreasonable design of the initial support and an increase in construction costs (Cui et al., 2019; Zhou et al., 2021).

Some experts and scholars begin to optimize the excavation and support parameter of super-large section highway tunnel regarding the above problems. Based on the support concept of tunnel "pre-built structure method", (Yuan et al., 2008) proposed a new type of pre-built prestressed structure support system for super-large section and low flat-ratio highway tunnel, which uses "prestress + grouting" to eliminate tensile stress in part of the area at the top of the tunnel, to adjust the load distribution of the support structure. (Pan et al., 2019) explored the failure mechanism of surrounding rock and the mechanical characteristics of support components of a small spacing tunnel with a super-large section using the geo-mechanical model test. (Zhao et al., 2021) summarized that the contact between initial support and middle partition is mainly tensile stress, and the middle and bottom parts of the supporting structure are mainly compressive stress in large-section loess tunnel. (Luo et al., 2021) studied the time-space law of supporting structure deformation in the shallow section tunnel by analyzing the primary support structural force of 18 sections in a large-span loess highway tunnel group, and finally designed the supporting parameters for large-span loess highway tunnel. (Zhou et al., 2011) studied the deformation and three-dimensional effect of supporting structure caused by the excavation of super-large section tunnel with double side heading method, and obtained that the excavation of the lower bench in the left drift and the bench in the core rock significantly affected the deformation and stress of the supporting structure, which is an essential process for the stability control of the support.

In recent years, the author's team has carried out a comprehensive study on the mechanical properties of the initial support structure of the super-large section highway tunnel by using laboratory tests and numerical calculations. The results showed that appropriately changing the arch spacing under the general surrounding rock conditions can ensure the bearing capacity of the initial support and improve the load sharing ratio between the steel skeleton and the shotcrete (Gao et al., 2019; Qi et al., 2019). Therefore, this paper puts forward a support scheme of optimizing the arch spacing for the initial support and sets up the comparative field test to study the differences between the original scheme and the optimized scheme in bearing mechanical properties and controlling tunnel stability.

2. Design of field test scheme
2.1 Engineering geological condition

Magongci tunnel is the first single-hole four-lane highway tunnel with the largest excavation section in Shandong Province, with an excavation span of 21.96 m and shallow buried depth. The mileage of the tunnel test section is YK104+500 ~ YK104+560, and the buried depth is about 48 m. The tunnel passes through the medium weathered limestone with mud stratum, and karst fissure water exists locally, which belongs to grade IV surrounding rock. The sketch of tunnel depth and geological section is shown in Figure 1.

2.2 Initial support scheme design

The tunnel is a three-centred circle with a cross-section width of 21.96 m and a height of 13.98 m. The initial support adopts bolt-shotcrete support, which consists of I20b steel arch, Φ 25 mm longitudinal connecting bars, Φ 8 mm steel-meshed, Φ 25 mm × 4 m hollow grouting anchor, 28 cm thick C25 shotcrete and Φ 50 mm advance small pipe. The optimized scheme is as follows: the arch spacing was adjusted from 100 cm to 120 cm. Furthermore, the longitudinal connection bars spacing was adjusted from 100 cm to 50 cm to enhance the bond performance between steel skeleton and shotcrete. Other support measures remain unchanged.

2.3 Field test and monitoring

The length of the test section of the Magongci tunnel is 60 m: YK104+500 ~ YK104+560. The original scheme of initial support is arranged in two testing sections: YK104+505 and YK104+516, and the optimized scheme of initial support is arranged in two testing sections: YK104+545 and YK104+555. The clearance convergence, vault settlement, surrounding rock pressure and arch stress were obtained through field monitoring. The tunnel deformation characteristics, surrounding rock pressure release law and arch stress distribution rule under the two supporting schemes were compared and analyzed. Figure 2 is the arrangement of testing points.

3 Test results and analysis
3.1 Comparative analysis of clearance convergence

Figure 3 shows the clearance convergence curves. The average clearance convergence of the original scheme was 11.24 mm, and that of the optimized scheme was 11.65 mm, an increase of 3.65%, and the difference is slight. In the first 5 days, the convergence change rate of the two support schemes was relatively faster, and the accumulation reached more than 60% of the total convergence. From 6 to 15 days, the convergence change rate tended to be stable. After 15 days, the convergence change rate of the two support schemes was less than the standard of 0.2 mm/d, and the clearance convergence was stable. The clearance convergence difference between the two support schemes is slight, and the convergence rate of the two support schemes has no noticeable time difference effect. Therefore, both two support schemes can ensure the stability of the tunnel in a short time.

3.2 Comparative analysis of vault settlement

The average vault settlement of the original scheme was 17.04 mm, and that of the optimized scheme was 18.01 mm, an increase of 5.69%, as shown in figure 4. In the first 15 days, the settlement change rate of the two support schemes was maintained at a high level, showing a ladder change of "increase-slow-increase-stable", and the accumulation reached more than 90% of the total settlement. After 15 days, the settlement change rate of the two support schemes was less than the standard of 0.2 mm/d, and the settlement was stable. The laws of vault settlement and settlement change rate of the two support schemes are the same as those of clearance convergence and convergence change rate,
which can better control the deformation of the tunnel and ensure the stability of the tunnel in a short time.

3.3 Comparative analysis of surrounding rock pressure

Figure 5 shows the surrounding rock pressure. The surrounding rock pressure of the two support schemes presented the distribution characteristics of "big up and down, small in the middle", the vault was the largest, the waist was the second, and the shoulder was the smallest, which indicates that the surrounding rock of the vault is disturbed the most after the tunnel excavation. The surrounding rock pressure of the optimized scheme was greater than that of the original scheme, and the average growth rates of testing points were: the vault 10.07% and the spandrel 18.34%, and the waist 2.96%. It can be considered that the internal deformation degree of the surrounding rock is the same under the two kinds of support constraints.

Figure 6 shows the surrounding rock pressure curves of the vault. In the beginning, the initial values of the surrounding rock pressure change rate of the original scheme and the optimized scheme were 62.97 kPa/d and 68.56 kPa/d, respectively. After 10 days, they decreased to 14.28 kPa/d and 19.65 kPa/d.
kPa/d, respectively, and the accumulation accounted for more than 84% of the total. After 15 days, the change rate of the surrounding rock pressure of the two support schemes gradually decreased to near 0, and the surrounding rock pressure was stable. It can be seen that the original rock stress of surrounding rock is released in a short time after tunnel excavation and then gradually stabilized by the constraint of the support structure. The load release law of surrounding rock under two kinds of support constraints was the same.

3.4 Comparative analysis of arch stress

Except that the reinforcement stress gauge of the right spandrel of section Y104+516 was damaged, the arch stress presented the distribution form of "big up and down, small in the middle", which was consistent with the distribution characteristics of surrounding rock pressure, and the arch stress of testing point was compressive stress, as shown in figure 7. The arch stress of the optimized scheme was less than that of the original scheme, and the average reduction rates of each testing point were: the vault 5.60%, the spandrel 11.18% and the waist 1.02%. The maximum stress appeared at the vault of Y104+516, which was 202.97 MPa, about 49.6% of the yield strength of steel. The minimum stress appeared at the left spandrel of Y104+545, which was 66.75 MPa, only 16.3% of the yield strength of steel. The initial support has enough strength reserve.

![Figure 7](image)

Figure 7 shows the arch stress curves of the vault. The variation law of arch stress was consistent with that of surrounding rock pressure. In the beginning, the stress change rates of the two supporting schemes were 32.41 MPa/d and 36.04 MPa/d, respectively. After 10 days, they decreased to 6.88 MPa/d and 8.98 MPa/d, and the accumulation accounted for more than 80% of the total. After 15 days, the stress change rate of the two support schemes gradually decreased to near 0, and the arch stress was stable. Combined with the surrounding rock pressure variation law, the arch in the two supporting schemes can quickly play its skeleton bearing role in the initial support after installation and constrain the surrounding rock deformation well.
4 Conclusion

The results show that the clearance convergence, vault settlement, surrounding rock pressure and arch stress of the two support schemes were stable in about 15 days, and the variation law and distribution characteristics are the same. The clearance convergence, vault settlement and surrounding rock pressure of the optimized scheme were slightly higher than those of the original scheme, increasing by 3.65%, 5.69% and 18.34%, respectively. The arch stress of the optimized scheme was less than that of the original scheme, reducing by 11.18%. In addition, the maximum stress of the arch is about 49.6% of the yield strength of the steel. It can be seen that the original scheme and optimized scheme have enough strength reserve to resist the deformation of surrounding rock and ensure the stability of the tunnel in a short time. This study can provide engineering references for the construction of a super-large section highway tunnel.

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