Monitoring and analyzing the shallow-buried highway tunnel in the soft stratum

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Abstract. The large deformation is one of the important characteristics of the shallow-buried highway tunnel (SBHT) in weak strata. To analyze the deformation law, the monitoring of ground and vault subsidence of Yunfu Road tunnel under Caiyun North Road in Kunming is carried out. The influence of excavation on the temporal and spatial characteristics of the SBHT in weak strata are elaborated. Based on the monitoring results, the deformation characteristics of the surrounding rock are analyzed. What’s more, some effective measures to control the deformation of surrounding rock in tunnel construction are pointed out, and the basis for the optimization of support system is provided. The research results can guide and used for the construction of the SBHT passing through similar soil strata.

1. Introduction
At present, the shallow-buried highway tunnel (SBHT) are blossoming in many big cities of China. The engineering accidents do occur from time to time, such as the overall subsidence of the overlying strata in tunnel and collapse accidents, which attracts the attention of engineers. The surrounding rock pressure acting on the SBHT is the total or partial soil weight of overburden. The stratum pressure has close relation with the support stiffness. From the point of reducing ground settlement, it requires that the initial support should have a certain stiffness. The self-sustaining ability of surrounding rock is not fully considered in the design, which is contrary to the philosophy of maintaining and utilizing the self-supporting ability of surrounding rock advocated by the New Austrian Method.

Combined with the practice of abundant mountain tunnels and subway projects in China, the idea of the New Austrian Method has been inherited and developed, and the idea of the SBHT and a complete set of supporting technologies have been established. The principle of "pipe-shed in advance of support, strict grouting, short excavation, strong support, quick closure and frequent measurement” must be followed in the SBHT. Ding et al. [1] adopted the cross diaphragm method method and benching tunnel construction method, which could effectively control the ground settlement in the initial section of tunnel engineering. Chakeri et al. [2] studied the influence of mixed strata and fault zone types on surface subsidence in the tunnel heading. Zhou et al. [3-5] studied the variation of tunnel properties and soil deformation characteristics under different construction parameters. Shain [6] studied the transverse settlement of ground surface caused by tunnel construction through the centrifugal model test. The relationship between the width of the settlement tank and the maximum settlement of deep soil and the depth of soil is obtained. Marshall [7] gave an equation for estimating the influence of tunnel size, burial depth and volume loss on the shape of the settlement tank. Divall et al. [8] studied the arrangement of pipe-shed to improve soil stability. Zhang et al. [9-11] studied the
stress of the surrounding rock, deformation mechanism, space-time effect, stratum deformation mode and failure characteristics of the SBHT employing on-site monitoring.

In this paper, the on-site monitoring results of Yunfu Road Tunnel under Caiyun North Road in Kunming are comprehensively analyzed. The displacement of surrounding rock of the SBHT are investigated. The research results can enhance safety and improve the ability of risk prevention in tunnel construction. What’s more, it can enrich the thought and construction technology of the SBHT and have important guiding significance.

2. Engineering situation and geological conditions

The Yunfu Road Tunnel under Caiyun North Road in Kunming is 62m long and the average depth is about 6m. The building limit of the tunnel is 10.25m wide and 5.5m high, which is two-lane two-way. The Caiyun North Road is the main highway corridor of the city with eight lanes two-way, and the traffic volume has been saturated. Furthermore, there are 12 pipelines under the road surface on both sides of the highway, such as communication signal, two water supply pipes with diameters of 0.5m and 1.2m respectively. The Yunfu Road Tunnel under Caiyun North Road is constructed by the bench method and excavated in six sections. The frequent stress transformation causes many disturbances to surrounding rock during construction, which has a great influence on surface pavement and pipeline. To ensure the smoothness of Caiyun North Road and the safety of the pipelines under the road, two rows of 133mm large pipe-shed are used in advance support, and grouting is used to reinforce the stratum of tunnel heading. The initial support is consists of shotcrete, I-beam and steel mesh, and the secondary lining is composed of reinforced concrete with 100 cm thickness.

The statistical table of physical and mechanical indexes of each soil layer within the construction depth of the Yunfu Road Tunnel under Caiyun North Road is shown in Table 1. It can be seen that the soil stratum is soft and has poor self-stabilization ability in Table 1, which can easily cause water gushing, sand bursting, tunnel collapse and deformation.

| Layer number | Category of soil layer | Layer thickness /m | Water content ω/% | Specific gravity of soil Г₃ | Unit natural weight /kN m⁻³ | Void ratio e₀ | Compression coefficient α₁⁻² / MPa⁻¹ | Compression modulus E₄ / MPa |
|--------------|------------------------|--------------------|-------------------|-----------------------------|----------------------------|--------------|-----------------------------------|-----------------------------|
| 1            | Miscellaneous fill     | 1.3                | 42                | 2.73                        | 16.8                      | 1.019        | 0.73                              | 3.21                        |
| 2            | Clay                   | 3.1                | 51                | 2.75                        | 18.9                      | 0.813        | 0.56                              | 4.51                        |
| 3            | Peat soil              | 3.8                | 115               | 2.71                        | 16.3                      | 1.656        | 1.36                              | 1.46                        |
| 4            | Silty soil             | 5                  | 43                | 2.74                        | 19.1                      | 0.715        | 0.27                              | 8.16                        |

3. Monitoring scheme

According to the site conditions, the ground settlement observation points are arranged on the pedestrian crosswalk of K12+0 and K12+62, and the intermediate isolation zone of K12+31 at the Yunfu Road Tunnel under Caiyun North Road. The distance of the observation points within the tunnel boundary is about 3m, and the distance of the observation points outside the tunnel boundary is about 6m. The settlement observation points are laid on the vaults of the ①, ② and ③ sections of the tunnel, whose distance along the direction of tunnel excavation is about 6m. The position of ground and vault observation points on the same section corresponds basically, which is convenient for comparative analysis. The specific burial location of the above observation points is shown in Figure 1. According to the tunnel construction condition, the monitoring frequency is adjusted dynamically to understand the deformation law and guide the construction of the SBHT in the soft stratum.
4. Analysis of observation results

4.1. Analysis of ground settlement

The final settlement of the ground observation points is shown in Table 2. The trend of ground deformation and the time history curve of the ground settlement are shown in Figures 2 and 3, respectively. The tunnel is divided into six parts and excavated sequentially. As can be seen from Figure 2, when the part ① of the tunnel is excavated at section K12+31, the settlement of observation point OP3 is the largest. When the part ② of the tunnel is excavated, the settlement of observation point OP5 is the largest directly above the section. When the part ③ of the tunnel is excavated, the settlement of observation point OP4 is the largest at the site directly above. When the parts ①, ② and ③ of the tunnel are excavated, the settlement of observation points OP3, OP4 and OP5 above the tunnel excavation area has exceeded 40m, and the maximum settlement of OP4 is 55mm. The settlement of observation points OP1, OP2, OP6 and OP7 outside the tunnel excavation limit is much smaller, all of which are less than 20 mm. When the lower section of the tunnel ④, ⑤ and ⑥ is excavated, the settlement variation of the surface observation points is similar to that of the upper section.

Table 2. The final settlement table of observation points.

| Observation points | OP1 | OP2 | OP3 | OP4 | OP5 | OP6 | OP7 |
|--------------------|-----|-----|-----|-----|-----|-----|-----|
| S/mm               | -8  | -38 | -83 | -97 | -73 | -34 | -6  |
Combining with the site construction situation, the monitoring data are analyzed, and the following results are obtained. Firstly, the ground subsidence of the SBHT in weak strata is mainly caused by excavation. The range of ground subsidence is relatively small, and it gradually diffuses from the center to both sides. The ground subsidence mainly concentrates on the top of the excavation area. Secondly, the maximum ground subsidence point OP4 is located directly above part ③ of the middle guide tunnel. The excavation of part ③ of the intermediate pilot tunnel has the greatest influence on the ground settlement. Therefore, when excavating part ③, the excavation footage of the intermediate pilot tunnel should be reduced appropriately, and timely support must be provided after excavation. Thirdly, when the distance between the tunnel face and the monitoring section K12+31 is about 2 m, the ground observation points of the monitoring section will subside. When the tunnel face passes through the monitoring section with 5 m, the settlement rate decreases and tends to be stable. When a certain part excavates under the section, the subsidence-time history curve of the ground observation points appears obvious step shape. Last but not the least, the excavation of the lower section causes the second large subsidence of the surface observation points, which is mainly because the large-scale excavation of the cavern has broken the original stress field. The water accumulated in the cave further
reduces the bearing capacity of the original soft soil layer, which results in the continued subsidence of the ground.

On the whole, the surface subsidence is large due to the influence of tunnel excavation. There are obvious settlement grooves in the driveway of the Caiyun North Road, which seriously affects traffic safety. Because the soil layer is loose, the grouting leakage is serious when grouting roadbed. The grouting pressure is small, and the lifting effect is not obvious. Therefore, the construction unit timely paved the road surface with asphalt to maintain the smoothness of the road surface and ensure the normal operation of the Caiyun North Road. During the excavation of part ④ of the lower section, the seepage of the water supply pipe increases obviously. To avoid the water pipe bursting accident, the construction unit timely arranged personnel to excavate the water supply pipe above the tunnel and reinforce the joint.

4.2. Analysis of vault settlement

The curves of settlement variation along the tunnel mileage at the observation points ①, ② and ③ of the vaulted roof are shown in Figure 4. The settlement of the measuring point of the vault is the largest from Figure 4. This is mainly attributed to the first excavation of part ①, and the excavation of parts ② and ③ also have a certain impact on it.

![Figure 4. The longitudinal distribution curve of tunnel vault settlement.](image)

The settlement-time history curve of the vault at section K12+31 is shown in Figure 5. When part ① and part ② are excavated, the excavation of the section is smaller from Figure 5. Therefore, the settlement of observation points at part ① and ② vault is small in the initial stage and stable rapidly. However, when part ③ is excavated at section K12+31, the rapid increase of transverse excavation dimension causes the rapid settlement of observation points at part ① and part ② vaults. The excavation of part ④ at the lower section mainly causes the settlement of the vault observation points of part ① and ③, and the settlement variation of the vault observation points of part ② is relatively small. Similarly, the excavation of part ⑤ of the lower section mainly causes the settlement of the observation points at the vault of part ② and part ③. The settlement variation of the observation point at the vault of part ① is relatively small. When part ⑥ of the section is excavated, the observation points of the vault at parts ①, ② and ③ all appear larger settlement. When each part of the section is excavated, the observation points of vault undergo the process of "rapid change - slow change - basically stable." Because of the longest settlement time, the settlement of the vault at part ① is the largest, which is 67 mm affected by the excavation of the rear parts.
Figure 5. The time-history curve of vault settlement measured at K12+31 section.

It can be seen that the two curves have similar linear patterns with time from Figure 6, which reflects the synchronous relationship between ground settlement and vault settlement during tunnel excavation. Because of the multi-part excavation of the tunnel, it takes a long time to realize the closure of the tunnel support, and the excavation is significantly affected by the space-time effect. Besides, the soft stratum and water accumulation in the tunnel reduce the bearing capacity of the soil layer, which results in large ground settlement and vault settlement. During the excavation of the lower section, the seepage during construction dewatering is easy to entrap fine silt particles. The consolidation and soil particle loss result in a slightly larger change of ground settlement than that of vault settlement.

Figure 6. The subsidence-time history curve of ground observation points and vault at section K12+31.

5. Conclusion
The measured data of ground subsidence and vault subsidence show stepped growth, which indicates that each excavation has a certain impact on the whole tunnel. As a whole, the ground settlement caused by the excavation of the upper section is larger than that caused by the excavation of the lower section. The settlement effect caused by excavation in the middle part ③ of the tunnel is the greatest.
The variation trend of ground settlement and vault settlement is the same in the same section, which reflects the synchronous relationship between ground settlement and vault settlement during tunnel excavation. Because the tunnel is excavated by six steps, the time for tunnel support to achieve closure is long, and the excavation is significantly affected by the space-time effect. The water accumulation reduces the bearing capacity of the foundation in the tunnel, which results in larger ground settlement and vault settlement. The soft stratum, soil consolidation caused by construction dewatering and soil particle loss results in a slightly larger change of ground settlement than that of vault settlement. Therefore, it is necessary to achieve "short excavation, strong support and quick closure" to effectively control settlement for the SBHT in weak strata.

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