THE STUDY ON THE THRESHOLD OF COVER DEPTH OF LARGE SECTION LOESS TUNNEL

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ABSTRACT

The method of load calculation in a tunnel is adopted by the state of covering depth. Due to the characteristics with macropore in loess stratum, the existing demarcation regulations of deep and shallow tunnels are inappropriate for the large section and shallow loess in highway tunnels. To determine the load of large section loess tunnel and provide a proper reference for structural design, the theoretical basis for distinguishing depth of deep and shallow tunnels as well as the characteristics of common calculation methods of surrounding rock load on depth are analysed. In this paper, a method distinguishing the threshold of cover depth of deep and shallow tunnels by coefficient of lateral pressure at the centre line of vault is put forward, in which the calculated results are consistent with the on-site findings. It can be concluded that the surrounding rock pressure in a deep tunnel is deformation pressure, while the surrounding rock pressure in a shallow tunnel is loosening pressure.

Keywords: Loess tunnel, threshold of cover depth, calculation methods of surrounding rock

1. INTRODUCTION

The continuous improvement of China's highway and railway transportation system demands that a large number of tunnels to be constructed in the loess strata. However, due to the macropore characteristics of loess soil and structural features (Lin & Wang, 1988), the surrounding rock pressure is different in loess tunnel than that in rock. Several problems generally occur in the construction of loess tunnels. Many technical challenges appear during construction and operation, such as lining cracks, water seepage, tunnel collapses, and even surface cracks in shallow tunnels. The reason for the emergence of these technical challenges is that they are caused by the inadequate understanding of the surrounding rock as well as the fact that the surrounding rock pressure, used at the design stage of the lining structure, is not the same as in the actual model. After tunnel excavation, along with the release of surrounding rock stress, the rock around the cavern deforms into the tunnel. The deformation of the surrounding rock is restrained after the support structure is applied, and the load acting on the support structure is also generated, that is, the surrounding rock pressure.

Generally, for shallow underground caverns, the rock mass at the crown will usually experience excessive settlement after excavation, and some rock masses may even collapse or fall off (Cheng, 2012). On the basis on this form of deformation, a calculation method based on stress transfer and pillar self-weight has been proposed. In deep underground caverns, following excavation and due to the existence of tensile stress at the top of the cavern, some of the rock masses lose their stability and slip downward and eventually collapse takes place. Numerous engineering practice and experimental results show that the rock mass after collapsing to a certain extent will no longer slide downward and is in a new equilibrium state. Therefore, the surrounding rock pressure in deep tunnels is usually not related to the burial depth.

In addition, it should be mentioned that diverse methods are existed for calculating the surrounding rock pressure. The assumptions are different and the type of surrounding rock used is also different. Commonly used calculation methods for rock pressure are mostly based on an assumption that the surrounding rock is regarded as a loose medium for theoretical analysis (Terzaghi, 1946; Qu & Li, 2011). For the determination of deep and shallow tunnels, a demarcation method contains three steps, which are presented as follows: (1) whether the load-bearing arch can be formed; (2) the calculation formula reaches the maximum; (3) empirical judgment.

At present, in China, for the surrounding rock pressure and the definition of the deep and shallow loess tunnels, the loess stratum is often studied as a loose medium (Li et al., 2016). This paper reviews the existing calculation methods of China for surrounding rock pressure and the method of threshold of cover depth, and discusses the applicability of the loose medium-based calculation method of surrounding rock pressure and the threshold of cover depth in the loess tunnel based on loose medium. Furthermore, the latest research results derived by other scholars are presented and a reliable and new method for demarcation of threshold of cover depth is proposed.

2. CALCULATION METHODS OF SURROUNDING ROCK PRESSURE

2.1 Terzaghi’s Theory

In the Terzaghi theory (Terzaghi, 1946), it is assumed that the rock mass is a loose medium, while it contains certain cohesive force. When the supporting structure is subjected to overlying pressure, flexural deformation occurs, causing displacement of the block, as shown in Figure 1.

Terzaghi expressed that the tunnel pressure is made by the gravity transfer of all strata in the upper part of the tunnel, and the pressure is correlated with the gravity of the cover rock, the friction coefficient, and cohesion of rock masses on both sides. The calculation formula for surrounding rock pressure is,

$$q = \frac{\gamma a_1 - c}{K_0 tan\varphi}\left(1 - e^{-\frac{K_0 tan\varphi}{a_1}H}\right) \tag{1}$$

And,

$$a_1 = \frac{B}{2} + h\, tan\left(45° - \frac{\varphi}{2}\right) \tag{2}$$

Where: q is the vertical uniform load acting on the supporting structure, γ is the surrounding rock density, H represents the depth of the tunnel, a_1 is the half span of arch, B is net span of the tunnel, h denotes net height of the tunnel, φ denotes the real internal friction angle of the rock mass, c is the cohesion of the rock mass, and K_0 is the lateral pressure coefficient of the rock mass.

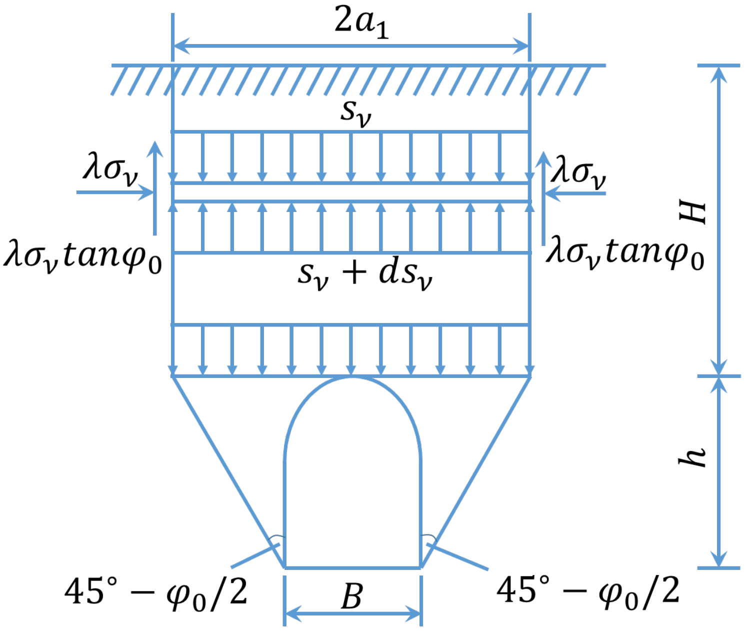

Figure 1: Calculation procedure based on Terzaghi's theory

When Terzaghi's theory is used to calculate soil pressure, the soil pressure tends to be constant when the soil cover thickness, H, is not less than $5a_1$ ($H \geq 5a_1$) (Qu & Li, 2011), which is typically utilized as the threshold of cover depth.

2.2 Protodyakonov's Theory

Protodyakonov's theory represents the situation that the rock mass, after being cut by joints, forms loose rock mass after excavation, while it still has some adhesive forces. After the tunnel excavation, the rock mass of the tunnel will form a load-bearing arch (Qu & Li, 2011). At the side wall of the cavern, two sliding surfaces are generated along the direction of $45° - \varphi_0/2$ with the side wall. The diagram of calculation process is shown in Figure 2. The surrounding rock pressure acting on the top of the cave is only the weight of the rock mass in the load-bearing arch. The formed rock mass of the load-bearing arch can only bear the compressive stress, and cannot bear the tensile stress.

$$q = \gamma h_k \tag{3}$$

$$h_k = a_1/f \tag{4}$$

$$a_1 = \frac{B}{2} + h\tan\left(45° - \frac{\varphi_0}{2}\right) \tag{5}$$

$$f = \frac{\tau}{\sigma} = \frac{(\sigma tan\varphi + c)}{\sigma} = tan\varphi + \frac{c}{\sigma} = tan\varphi_0 \tag{6}$$

Where φ_0 denotes the calculate friction angle of the rock mass, f is the rock solidity coefficient, and τ represents the shear strength of rock mass.

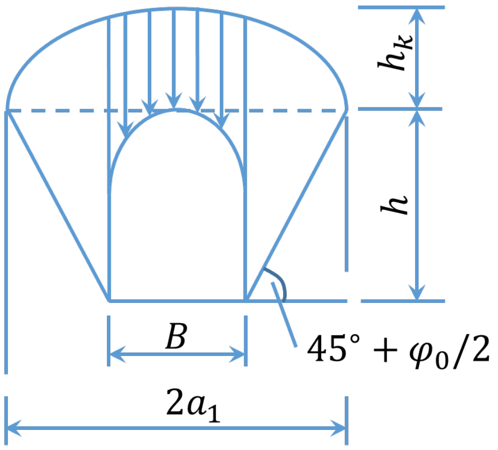

Figure 2: Calculation process diagram of Protodyakonov's theory

According to the Protodyakonov's theory, the relationship for threshold of cover depth H_P is as follows,

$$H_P = (2.0\sim2.5)\frac{b_t + H_t \tan\left(45^\circ - \frac{\varphi_0}{2}\right)}{f} \tag{7}$$

2.3 China's Code for Design of Road Tunnel

China's "Code for Design of Road Tunnel (CDRT) (2004)" is based on the statistics of tunnel collapse (Guan 1979). The range and shape of the collapse under different surrounding rock classification levels, and the rock mass in the landslide area are taken into account as the tunnel load values. The calculation formula of the load of loose surrounding rock in deep buried tunnel is as follows,

$$q = 0.45 \times 2^{s-1} \times \gamma\omega (kN/m^2) \tag{8}$$

Where s is classification level of surrounding rock in CDRT (the rock classification method combines qualitative and quantitative analyses, taking into account the rock strength, rock integrity, groundwater, initial stress, and joint surface. A brief illustration is available in Appendix A), γ is rock density, $\omega = 1 + i(B-5)$ is the influence coefficient of the width, B is tunnel width, i represents variation of surrounding rock pressure with B's variation. Herein, B = 5m is adopted as a benchmark. When $B < 5m$, consider $i = 0.2$, and when $B > 5m$, take in to account $i = 0.1$.

In accordance with CDRT, the threshold of cover depth is as follows,

$$H_P = (2\sim2.5)h_q \tag{9}$$

H_P is the threshold of cover depth, $h_q$is load equivalent height. The formula is as follows,

$$h_q = \frac{q}{\gamma} = 0.45 \times 2^{s-1} \times \omega (kN/m^2) \tag{10}$$

Consequently, it can be seen that these theoretical equations can be roughly divided into two main categories: one of which is based on the equation $q = \gamma h$, such as Protodyakonov's formula and Terzaghi's equation, their difference lies only in the method and principle of choosing an equivalent thickness h. The influencing factors of surrounding rock pressure, considered by this kind of method, are relatively simple, which is convenient for engineers to carry out the actual engineering calculations.

The other is based on the rock classification system (Q or RMR), such as China's CDRT. These formula takes into account several influencing factors and can more comprehensively reflect various mechanical properties of surrounding rock. However, due to consideration of many indicators, some of the indicators do not easily achieve or have greater arbitrariness in the actual project, thus the results of calculation are significantly affected by the subjective consciousness.

3. APPLICABILITY OF CALCULATION FORMULAS IN LOESS TUNNELS

A numerical example is given to illustrate the applicability of several formulas for calculating the pressure of deep and shallow burial rock in the present loess tunnel.

Xinzhuangling Tunnel, located in Yuzhong County, Lanzhou City, Gansu Province, China, is in the loess strata. The physical and mechanical parameters of the rock mass are as follows: cohesion 26 kPa, bulk density 1.62 g/cm^3, friction angle 27°, tunnel width 14 m, and tunnel height 8 m. According to the mentioned formulas, the results of the threshold of cover depth are listed in Table 1.

Table 1: The results of the threshold of cover depth with different formulas

Methods	Terzaghi’s Formula	Protodyakonov's formula	CDRT
The threshold of cover depth	59.5m	33.9m	68.4m

Among these results, the Protodyakonov's formula contains the lowest threshold of cover depth, while the threshold of cover depth of the CDRT is the largest. The results of the CDRT and the Terzaghi’s Equation are close. The depth of the Xinzhuangling Tunnel is 83 m and greater than the threshold of cover depth by the three previous methods. According to the above-mentioned formulas, the tunnel is denoted as a deep tunnel by all means. However, through field investigation, there was a crack in the ground above the tunnel. Even with a depth of 83 m, tunnel excavation still possesses a significant impact on the overburden up to surface, indicating that the surrounding rock pressure of the loess tunnel does not form a load-bearing arch.

4. DISCUSSION

The threshold of cover depth has always been an academic and engineering concern, and the demarcation criteria is crucial to judge the nature of the surrounding rock pressure of the tunnel lining. One view is that in the tunnel construction, the depth in which load-bearing arch can be guarantee can be defined as the threshold of cover depth, which is determined from the perspective of loose load. Another view is that the influence range of surrounding rock relaxation, caused by tunnel excavation, cannot reach the depth of the earth surface, which can be defined as the threshold of cover depth. Additionally, this is the demarcation standard from the perspective of continuum mechanics in geotechnical engineering.

Zhao et al. (2003), based on continuum mechanics, proposed a numerical analysis method to define the depth of the tunnel by using the lateral pressure coefficient of the center line of

the tunnel crown. However, this method is only used to calculate the surrounding rock pressure, and does not provide a proper basis for confirming the threshold of cover depth.
In a study conducted by Hu (2015), through the statistical analysis of the deformation of loess tunnels, the significant results of deformation with tunnel depth are inconsistent between deep and shallow tunnels. According to the difference of significance level between deep and shallow tunnels, a method of defining the threshold of cover depth by statistical methods, whether the influence of tunnel depth on the deformation of surrounding rock is significant or not, is put forward. Based on the inadequate level of the cover depth in the statistical data, the threshold of cover depth is in the range of 45 to 95 m.

The statistical law of deformation with depth of loess tunnel represents that the deformation data of tunnel in shallow tunnel are relatively discrete, and the surrounding rock pressure is mainly loose load. The tunnel deformation with depth changes in deep tunnel with a certain regularity, and the surrounding rock pressure is mainly deformation pressure. Hence, it is proposed that in deep tunnel, the surrounding rock pressure is deformation pressure and shallow tunnel the surrounding rock pressure is loosening pressure.

5. CONCLUSIONS

The threshold of cover depth is the foundation of calculating surrounding rock pressure, and two views on threshold of cover depth have different applicable conditions. Whether the load-bearing arch can be formed is usually used in rock tunnel, and, deformation pressure or loosening pressure, is more applicable in loess tunnel. The threshold of cover depth on Protodyakonov's theory and CDRT are based on the rock tunnel, so they are inaccurate in loess tunnel. The threshold of cover depth according to Terzaghi theory is based on the loosening pressure, which does not fit with that the condition of surrounding rock pressure in loess ground is deformation pressure in deep cover. The relationship between the lateral pressure coefficient of the center line of the tunnel crown and cover depth and the relationship between the deformation and cover depth give new ideas for exploring the critical burial depth with the perspective of mechanics and deformation respectively.

APPENDIX A: CLASSIFICATION SYSTEM OF CHINA'S CDRT

Table 2: Classification table for the CDRT

Rock grade	I	Ⅱ	Ⅲ	IV	V	VI
[BQ]	> 550	550~451	450~351	350~251	≤ 250	Soft plastic clay

$$[BQ] = BQ - 100(K_1 + K_2 + K_3)$$

$$BQ = 90 + 3R_C + 250K_V$$

$$K_V = \left(v_{pm}/v_{pr}\right)^2$$

R_C denotes uniaxial saturated compressive strength of rock, v_{pm} is elastic longitudinal wave velocity of rock mass, v_{pr} denotes elastic longitudinal wave velocity of rock, K_1 is influence correction coefficient of groundwater, K_2 is influence correction coefficient of the main weakness surface, and K_3 is influence correction factor of initial stress state.

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