Research on the Stress Variation Effect of Overburden Loads in Utility Tunnel Roof

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Abstract. As an underground structure, the utility tunnel is subjected to the pressure of overburden soil. Calculation of the overburden pressure soil are different when the burial depth changes. In this paper, the calculation methods of soil loads are summarized. In view of utility tunnel, the ANSYS finite element analysis is adopted to analyze the pressure of the roof. When calculating the structural stress, the working condition is considered as the backfill after the excavation of the soil. Considering the stress variation of the roof edge of the structure with different burial depth, it can be found that compressive stress at 1/2 span is about 1.7-2.2 times of the tensile stress at the corner. With the increase of burial depth, the rate of increasing roof stress value decreases. When the burial depth reaches a certain depth, soil arching effect plays a role and the roof stress value tends to be stable. Some suggestions are given to the designers of the utility tunnel which can reduce the waste of building materials.

1. Introduction
Utility tunnel refers to a modern intensive urban infrastructure, which lays the communication pipeline, water supply and drainage and other concentrated underground pipeline in the same artificial space. It is an important infrastructure of city running "lifeline", can effectively improve the comprehensive carrying capacity of cities and promote the development of urbanization process.

There are few researches on the utility tunnel in China, so the construction technology and structural design of are still in the initial stage. The calculation method of overburden load is not given in current code. In-depth research of structure design on utility tunnel can provide suggestions for the construction of urban, promote the development of utility tunnel and improve the efficiency of resource utilization.

In the general structural design method, the mechanical model of utility tunnel is assumed to be a closed frame, and various loads are applied on the frame. The interaction between soil mass and utility tunnel is expressed by overlying soil pressure and lateral soil pressure.

In China’s current code, there is no provision for the method of determining overburden load in structural design. Most designers, when carrying out structural design, adopt the conservative design method which is partial to safety, resulting in unnecessary waste of materials and increase of construction period.

RongZe [1] et al. analyzed the calculations of design of utility tunnel, including load statistics and calculation, model selection and internal force calculation. The method to evaluating the car loads is the difficulty in the design and calculation of the utility tunnel. Shortcoming of the paper is that the overlying soil load of utility tunnel was calculated directly according to the whole soil column theory without considering the effect of soil arching and lateral earth pressure on the structure.
Based on the municipal road projects in Pingtan county, Fujian Province, a numerical simulation model for stress distribution of utility tunnel based on the fast Lagrangian analysis of continua in three dimensions (FLAC3D) [2] is established. By changing the buried depth of utility tunnel, the vertical stress of each position is monitored. Then, an estimated formula is obtained, which shows the relation between the stress of key positions and the upper loads.

Wang Lingxian [3] et al. focuses on a practical utility tunnel which is built under the road and includes beam and column construction in Zhengzhou city, in which the mechanical property of the whole structure and related members have been analyzed using finite element software ABAQUS, and various load combinations have been considered. In the whole modeling process, the overlying soil load of the structure is calculated according to the whole soil column theory, and the influence of the buried depth of the utility tunnel on the overlying soil loads is not considered. Therefore, it is very necessary to study and analyze the calculation method of overburden pressure and lateral earth pressure on the utility tunnel.

2. Calculation theory of overburden load
As the utility tunnel is under the ground, the interaction between soil and structure has a great impact on the stability and reliability of the structure. Overburden load of roof and the lateral soil pressure of side plate constitute soil loads, which relate to physical properties of soil and differ from each other.

Overburden load is affected by the buried depth of utility tunnel for the soil arching effect. Lateral load is related to the height of underground water level.

2.1. Whole soil column theory
The whole soil column theory [5], that is, vertical soil pressure is the weight of the whole soil column on the roof of the structure. In this theory, the load of overburden is affected by the depth of the structure and the density of overburden.

\[ q = \gamma H \]

where \( q \) is the overburden load, \( \gamma \) is the density of soil, \( H \) is the buried depth of utility tunnel. When the soil is layered, the overburden load is the sum of density of each soil multiplied by its thickness.

2.2. Platts formula
According to the concept of forming natural arch in loose formation, the calculation method of overburden load is as follows:

\[ q = \gamma h_p \]

\[ h_p = b/f, \quad b = h + H \cdot \tan(45 - \phi/2) \]

where \( q \) is the overburden load, \( \gamma \) is the density of soil, \( h \) is the height of natural arch, \( b \) is the half span of natural arch, \( f \) is the strength coefficient of soil. \( b \) is the half span of the tunnel, \( H \) is the height of the tunnel, \( \phi \) is the internal friction angle of the soil. Due to not been included in the theory calculation formula of Platt’s pressure arch, and the result of calculation will be more safe.

2.3. Terzaghi theory
Terzaghi theory considers the effect of soil on the top of the structure [5]. The vertical pressure at any point in the soil on the top of the structure is:

\[ \sigma_v = \frac{\gamma b - c}{\tan \phi} \left(1 - e^{-\frac{\Delta \tan \phi}{b}}\right) \]

With the increase of the buried depth of utility tunnel, \( e^{-\frac{\Delta \tan \phi}{b}} \) is closing to zero, so \( \sigma_v \) tends to a fixed value.
\[ \sigma_v = \frac{\gamma b}{\tan \phi \lambda} \]

where \( \sigma_v \) is the vertical pressure at any point in the roof rock stratum, \( b \) is half span of the natural arch, \( \lambda \) is the lateral pressure coefficient, \( \phi \) is the internal friction angle, \( h \) is the buried depth of tunnel.

Based on the experimental results, Terzaghi summed up the result that \( \lambda = 1 \sim 1.5 \). Supposing \( \lambda = 1 \), the formula becomes the following form.

\[ \sigma_v = \frac{\gamma h}{\tan \phi} = \frac{\gamma b}{\tan \phi} \]

For sand, \( c = 0, \lambda = 1 \) then \( \sigma_v = \frac{\gamma b}{\tan \phi} \). Considering \( c \), \( \sigma_v \) is actually less than the calculated value. When \( \phi \) gets the internal friction angle, \( f_i = \tan \phi \). The calculated results are the same as those of Platts formula.

2.4. Comparison of theories

The reliability of the whole structure is determined by the method of calculating the overburden load of the roof. The Platts formula requires that the natural balance arch can be formed on the top of the cave after excavation. Its application condition is that the soil must have a certain self-bearing capacity and usually used in structures with large burial depth and soil with high strength. The calculation results of the whole soil column theory and the Terzaghi formula are that the overburden load increases with the increase of the depth of the structure. The difference between them is that the overburden load of the whole soil column theory keeps increasing linearly, while the value of overlying load in the Terzaghi formula tends to be stable gradually. The whole soil column theory is the most conservative of the three theories, and it is suitable for shallow buried structures. The Terzaghi formula can reasonably reflect the mechanism of overlying soil load, so it has a wider application range.

3. Finite Element Analysis

In this paper, ANSYS finite element analysis software is used to establish the integral model of the utility tunnel and surrounding soil. When calculating the structural stress, the working condition is considered as the backfill after the excavation of the soil, and then the stress variation of the roof edge of the utility tunnel is analyzed.

3.1. Geometric Parameter

This paper simulates and calculates the upper load of the utility tunnel under the burial depth of 4m, 8m and 12m. The geometric parameters of the structure are that the width is 8m and height is 4m. The whole model includes the utility tunnel and surrounding soil, and both adopt solid45 element.

Figure 1. Finite element model of utility tunnel
3.2. Constitutive properties of materials

The constitutive properties of surrounding soil material conform to Drucker-Prager yield criterion, which considered the volume expansion due to the yield criterion. Drucker-Prager yield criterion is suitable for granular materials such as soil and rock mass.

| layer                  | depth (m) | density (kg·m⁻³) | deformation modulus (MPa) | poisson's ratio | internal friction angle (°) | cohesion (kPa) |
|------------------------|-----------|-------------------|---------------------------|----------------|-----------------------------|----------------|
| Miscellaneous fill     | 0.4-1.19  | 1930              | 4.37                      | 0.2            | 14                          | 24             |
| Fine and medium sand   | 1.19-9.20 | 1740              | 2.49                      | 0.4            | 12                          | 11.7           |
| Soft soil              | 6.99-10.19| 1940              | 8.8                       | 0.4            | 13                          | 15             |

The structural model of utility tunnel is an elastic model without considering joints in which material is concrete, and the mechanical parameters are shown in the table below.

| density (kg·m⁻³) | deformation modulus (MPa) | poisson's ratio |
|------------------|----------------------------|-----------------|
| 2.8×10⁻³         | 5×10⁴                      | 0.2             |

In order to obtain the change of soil pressure under different burial depth in soft soil condition, when the thickness of overlying soil layer is 1H, 2H and 3H (H is the height of utility tunnel section). That is, the depth of overlying soil is 4m, 8m and 12m.

3.3. Overburden pressure on utility tunnel

Through ANSYS modeling and structural simulation, the overburden pressure on the top of the structure after excavation and backfilling at different burial depths is obtained. Stress nephogram of utility tunnel are as follows when overlying soil layer is 1H, 2H and 3H.

Figure 2. Stress nephogram of utility tunnel when buried 1 H
In order to study the effect of structural burial depth on the stress variation of the roof edge of utility tunnel, the stress values at the corner of the roof, 1/4 span and 1/2 span are selected in the simulation results. The stress values at these locations are plotted as polygons as shown in Figure 5.
4. Conclusion
From the stress nephogram of the utility tunnel, it can be seen that the roof is obviously restrained by the side plate. Under the action of overburden soil load, the roof appears larger tensile stress in corner and compressive stress in 1/2 span. The compressive stress at 1/2 span is about 1.7-2.2 times of the tensile stress at the corner, and the ratio increases with the increase of the buried depth of the structure.

It shows that with the increase of buried depth, the stress difference on the top of the utility tunnel becomes larger and larger.

Although the stress value of the roof edge increases with the increase of the buried depth of the structure, it can be seen from the broken line diagram that the rate of stress increase has been decreasing. At this time, considering that the buried depth is increasing, soil arching effect gradually takes effect. When the buried depth is deep enough, the stress value of the top edge will tend to be stable, and there will be obvious arch foot in the surrounding soil.

When calculating the reinforcement of the structure, designer should take into account the change of the load on the roof, i.e. the tension stress on both sides of the roof and the compression stress in the span. When reinforcement is used, different reinforcement quantity can be considered for both sides of roof and mid-span section of utility tunnel. When the buried depth of the structure reaches a certain depth, it is not accurate to calculate the upper load by using the theory of whole soil column, which will make the calculation result larger and cause waste of materials. In this case, the size of the upper load under the influence of soil arching effect should be solved through the finite element calculation software of the structure.

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