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Abstract

Soil arching effect; Expanding arch; Triangular slip surface; Limit equilibrium; Tunnel earth pressure

Full Text

Study on Calculation Method of Tunnel Earth Pressure Considering Expanding Arch Effect

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Abstract

During tunnel excavation, considering the form of the tunnel's potential slip surface and combining it with the development law of stratum arch effect, this study proposes a triangular slip surface model that comprehensively considers the expanding arch effect. This model is used to derive and calculate tunnel earth pressure under limit equilibrium conditions. Through numerical examples, the influence of model parameters—including the cohesion reduction coefficient, sliding surface friction angle, and slip surface camber angle—on the calculated earth pressure is comparatively analyzed. Additionally, various limit equilibrium theories for tunnel earth pressure are examined to verify the applicability of the calculation model. The results demonstrate that the smaller the cohesion reduction coefficient, the greater the earth pressure calculated by the model. Similarly, the smaller the sliding surface friction angle, the greater the calculated earth pressure, while larger slip surface camber angles yield smaller calculated earth pressures. With increasing depth, earth pressure first increases and then decreases. In this modeling approach, the selection of the cohesion reduction coefficient plays a decisive role in calculating tunnel earth pressure. The earth pressure calculated using a cohesion reduction coefficient of 0.2 is similar to that calculated by other theories, demonstrating stronger applicability. Meanwhile, combined with analysis of the limitations and applicable critical depths of various loosening earth pressures, appropriate calculation methods should be selected according to the usage conditions and influencing factors of different earth pressures to provide a basis for accurate tunnel earth pressure calculation.

Keywords: Soil arching effect; Expanding arch; Triangular slip surface; Limit equilibrium; Tunnel earth pressure

Introduction

Tunnel engineering plays a vital role in urban infrastructure construction; however, the complexity of underground environments often makes earth pressure calculation challenging. During tunnel excavation, non-uniform deformation occurs above the tunnel, causing stress path transfer in the soil and leading to the soil arching effect, which influences tunnel surrounding rock pressure. Different stress paths generate geotechnical pressures that affect the selection of tunnel support systems and safe construction. Therefore, research on tunnel surrounding rock earth pressure calculation considering the soil arching effect is of significant importance for guiding tunnel design and construction.

In terms of model tests and numerical calculations, Chevalier [1-3] utilized trapdoor tests and discrete element software simulation to verify the existence of a pyramidal slip surface for soil failure through analysis of arching effects and load transfer mechanisms. Takemura [4] employed centrifuge tests to study the failure mode of shallow buried circular tunnels as a triangular arch, considering the variation 规律 of soil shear strength. Lei [5] investigated the failure mechanism and lining stress characteristics of shallow tunnels under eccentric loads through model experiments, analyzing the variation and distribution of surrounding rock pressure to determine that the collapse body above the tunnel is an inverted cone shape. Ma Lin [6] et al. considered the structural characteristics of surrounding rock and used FLAC3D to simulate the excavation process of loess tunnels, studying the influence of surrounding rock structure on tunnel earth pressure during excavation. Wang Zhiwei [7] used UDEC discrete element software and the limit analysis upper bound method to study calculation methods for loosening rock and soil pressure under different boundary conditions. Xu Weizhong et al. [8] used finite element software ABAQUS to study the formation mechanism and influence of soft soil arching effects under different shield burial depths. Bai Yanhui [9] investigated the differences in soil arching effects caused by stratum loss during shield excavation in Shanghai soft soil strata through numerical calculations, establishing the relationship between stratum loss and soft soil arching effects.

Regarding theoretical calculations, tunnel earth pressure changes with the soil arching effect. Engesser [10] proposed a calculation model for tunnel surrounding rock pressure based on upward concave arches, applicable only to relatively good surrounding rock conditions. Lou Peijie [11] considered the influence of downward concave arch curves on earth pressure and established a calculation method for loosening earth pressure of shallow tunnels under this arch curve. Zhu Menglong et al. [12] studied the loosening earth pressure of shallow tunnels with pyramidal slip surfaces based on incomplete soil arching effects. Wang Jiaquan et al. [13] determined the variation 规律 of triangular slip surfaces through trapdoor tests and, using the triangular slip surface as a mechanical model, derived an earth pressure calculation model through differential soil strip stress state analysis. Xu Changjie et al. [14] studied the loosening earth pressure of major principal stress trajectories with circular arch, catenary, and parabolic arch shapes.

This study aims to propose a triangular slip surface model that comprehensively considers the expanding arch effect of soil arching for tunnel earth pressure calculation. Considering that the progressive development of soil arch slip surfaces significantly influences the loosening earth pressure above the tunnel, a loosening earth pressure calculation model considering triangular slip surfaces is established using the limit equilibrium method to analyze the variation 规律 and applicability of earth pressure under triangular slip surfaces. Through theoretical calculations and actual engineering case analyses, the accuracy and practicality of this method are verified, providing important references for tunnel design and construction.

2.1 Development Law of Stratum Arching

Terzaghi [15-16] verified the existence of the soil arching effect through trapdoor tests, which develops with stratum changes. Iglesia et al. [17-18] analyzed the development of arching effects in soil layers through centrifuge model tests, proposing that stratum arching effects can be roughly divided into four stages with increasing stratum deformation: elastic stage, maximum arch, expanding arch, and limit arch, as shown in [Figure 1: see original paper].

In the elastic stage, the soil arching effect has not yet formed under slight stratum disturbance. As deformation further increases, soil at both edges of the trapdoor begins to yield, forming a stratum arch that develops upward along the trapdoor edges, entering the maximum arch stage. Under the stratum arch effect, stress from the upper soil transfers along the stratum arch. In the maximum arch stage, shear surfaces form at the trapdoor edges at angle α to the vertical plane, creating semi-circular or triangular stratum arches. With further deformation, the expanding arch stage is entered, where the angle between shear surfaces and the vertical plane further decreases, developing into triangular slip surfaces that penetrate to the ground surface and further evolve into trapezoidal shapes. When shear surfaces reach the vertical plane, the limit arch stage is formed, where the slip surface becomes rectangular.

2.2 Tunnel Slip Surface Form

[Figure 2: see original paper] shows the calculation model for loosening earth pressure of shallow buried tunnels. During tunnel construction, slip surface forms vary at different stages due to stratum deformation effects, while tunnel burial depth also significantly influences slip surface forms. The slip surface forms resulting from stratum deformation effects can be referenced from Iglesia's [17-18] stratum arch development, with the progressive stratum arch model shown in [Figure 2: see original paper]. For shallow buried tunnels with relatively small displacement, the soil arching effect cannot fully develop, and soil is not affected by the arching effect. For deep buried tunnels, the occurrence of soil arching effect changes the earth pressure above the tunnel as the slip surface shape develops.

3.1 Bierbaumer Theory

The Bierbaumer theory [19] proposes that during shallow tunnel excavation in loose rock mass, subsidence of tunnel crown soil drives subsidence of soil on both sides, ultimately forming sliding surfaces. For calculation convenience, the sliding surface is assumed to extend upward from the tunnel arch foot at a rupture angle, with the slip surface assumed to be planar, as shown in [Figure 3: see original paper].

Assuming that vertical pressure on the tunnel crown is primarily borne by the weight of overlying soil mass, a vertical slip surface forms in the overlying soil. During the sliding process, a vertical total pressure Q acts above the tunnel. The vertical pressure acting on the tunnel structure top is calculated through formulas (though the specific equation is corrupted in the original text).

3.2 Expanding Arch Earth Pressure Theory

Based on the development law of stratum arching, the expanding arch is the most important stage during the process between the elastic stage and limit deformation stage. The triangular arch expanding arch theory was first proposed by Bierbaumer [20]. This paper designs a calculation model considering expanding arch earth pressure based on triangular arch expanding arch theory. Assuming triangular slip surfaces form along the expanding arch top above the tunnel, expanding arch earth pressure analysis and collapse body force analysis are shown in [Figure 4: see original paper]. The slip lines above the tunnel are JG and JH.

Taking the collapse body JGH above the tunnel as the research object, its force analysis is shown in [Figure 5: see original paper]. According to Coulomb's earth pressure theory, using wedge bodies AHJ and BGJ as objects, the force

E1 acting on the collapse body is calculated (formula 3). Decomposing E1 along shear surfaces JH and JG yields normal stress N1 and tangential stress T1, directed obliquely downward (formulas 4 and 5). The shear force T is obtained from the Mohr-Coulomb strength criterion on the rupture surface, directed obliquely upward (formula 6).

To fully consider the influence of cohesion on the slip surface, a cohesion reduction coefficient λ is introduced. As earth pressure loosens, the friction angle on the slip surface cannot be fully mobilized, resulting in a slip surface friction angle smaller than the soil's internal friction angle. Substituting formula (4) into (6) yields the shear strength on rupture surfaces JH and JG.

According to the static equilibrium condition of collapse body JGH, the total earth pressure above the tunnel is obtained (formula 8). Substituting formulas (3) and (7) into formula (8) yields the total earth pressure above the tunnel, and the vertical pressure acting on the tunnel structure top is calculated (formula 9).

3.3 Limiting Arch Earth Pressure Theory

Under the action of a limiting arch, vertical slip surfaces form above the tunnel. The downward sliding of overlying soil is constrained by the confining effect of soil on both sides. The earth pressure above the tunnel equals the weight of overlying soil minus the side friction resistance on both sliding surfaces.

In this earth pressure calculation method, under the soil arching effect, the cohesion and friction angle on the slip surface directly influence the vertical pressure on the tunnel crown. Numerical examples are used to analyze the triangular slip surface earth pressure of the expanding arch effect.

3.4 Other Earth Pressure Theories

According to the "Code for Design of Highway Tunnels," earth pressure for shallow buried tunnels is divided into two cases: 1. When burial depth H is less than or equal to the equivalent load depth, the vertical pressure on the tunnel crown is treated as uniform pressure acting on the tunnel crown. This theory ignores friction resistance on slip surfaces and applies to very shallow tunnel earth pressure calculations. 2. When burial depth is greater than the equivalent load depth but less than a certain value, Xie Jiahuang's calculation theory [21] is applied.

4 Case Study

In the calculation method for triangular slip surface earth pressure considering expanding arch effect, the vertical pressure on tunnel structure top is primarily influenced by burial depth H, triangular slip surface cohesion reduction coefficient λ, and triangular slip surface friction angle δ. Taking an urban metro tunnel as an example, with tunnel excavation width 2a=6.2m, lining structure height h=6.5m, assuming a slip surface at the tunnel foot with angle α to the horizontal plane, overlying single soil layer with unit weight γ=19 kN/m^3, cohesion c=15 kPa, internal friction angle ϕ=30°, slip surface cohesion reduction coefficient λ, and friction angle δ. In triangular slip surface earth pressure calculations, the influence of various parameters is analyzed.

4.1 Influence of Slip Surface Cohesion Reduction Coefficient

The triangular slip surface differs from actual tunnel slip surfaces to some extent. The cohesion reduction coefficient λ is introduced for correction, assuming that cohesion is not fully mobilized during triangular slip surface deformation. To further investigate the influence of the cohesion reduction coefficient on earth pressure above the tunnel, the friction angle on the slip surface is assumed to be fully mobilized (δ=ϕ). The variation 规律 of earth pressure with burial depth under different cohesion reduction coefficients is studied, as shown in [Figure 7: see original paper].

As shown in [Figure 7: see original paper], triangular slip surface earth pressure first increases and then decreases with increasing depth. When tunnel burial is very shallow, the influence of cohesion mobilization on earth pressure is minimal. With increasing burial depth, smaller cohesion mobilization coefficients result in greater earth pressure. Full cohesion mobilization reduces earth pressure above the tunnel. Therefore, in practical engineering, considering full mobilization of slip surface cohesion to reduce tunnel earth pressure can ensure safe tunnel construction.

4.2 Influence of Slip Surface Friction Angle

The friction angle δ of the triangular potential slip surface directly affects the anti-sliding force on the sliding surface. Without considering cohesion influence, different values of slip surface friction angle δ are analyzed to determine its effect on earth pressure above the tunnel. The resulting earth pressure variation curves are shown in [Figure 8: see original paper].

As shown in the curves in [Figure 8: see original paper], with increasing tunnel burial depth, the extension of triangular slip surfaces and increasing lateral earth pressure on side soil wedges lead to increased friction resistance on slip surfaces. When the generated friction resistance exceeds the weight of the overlying sliding soil wedge, earth pressure reaches its peak value, gradually decreasing with further burial depth increases. Overall, earth pressure above the tunnel first increases and then decreases with increasing burial depth. In shallow tunnel sections, the slip surface friction angle δ has minimal influence on earth pressure, which is primarily provided by the weight of the overlying triangular wedge. With increasing δ, the friction resistance generated by normal stress on the slip surface increases, resulting in gradually decreasing earth pressure.

4.3 Influence of Slip Surface Camber Angle

The slip surface camber angle above the tunnel directly affects the range of sliding soil mass, inevitably influencing vertical pressure above the tunnel. Without considering cohesion reduction and friction angle effects on the slip surface, the variation 规律 of earth pressure with depth is calculated for different slip surface camber angles, as shown in [Figure 9: see original paper].

As shown in [Figure 9: see original paper], within a burial depth of 20m, the influence of slip surface camber angle on earth pressure is minimal. With further depth increases, larger slip surface angles result in slower earth pressure growth, eventually reaching maximum earth pressure. With increasing camber angle, secondary rupture surfaces may develop inside soil wedges on both sides of the tunnel, making this model unsuitable for calculating tunnel earth pressure. Therefore, calculating tunnel earth pressure with expanded camber angles has certain limitations and uncertainties.

4.4 Analysis of Various Earth Pressure Influences

Through analysis of slip surface cohesion reduction coefficient, slip surface friction angle, and slip surface camber angle influences on earth pressure, slip surface cohesion shows the most significant influence. To further compare and analyze various earth pressures, several existing limit equilibrium methods for tunnel rock and soil pressure calculation are compared to study the applicability of the triangular slip surface earth pressure proposed in this paper. With cohesion reduction coefficients λ=0, 0.1, 0.2, and 0.3, and slip surface friction angle δ, the variation 规律 of various limit equilibrium theory earth pressures with depth is analyzed, as shown in [Figure 11: see original paper].

As shown in [Figure 10: see original paper], earth pressures calculated by Bierbaumer and Xie Jiahuang formulas first increase and then decrease with depth. When exceeding critical depth, the surrounding rock pressure calculation results become inconsistent with actual conditions. Earth pressure calculated by Terzaghi's formula slowly increases with depth, eventually stabilizing. When λ=0 (without considering cohesion influence), the growth rate of earth pressure calculated by this paper's method gradually slows with increasing λ. Earth pressure calculated with λ=0.2 is similar to that calculated by other theories, demonstrating strong applicability.

Conclusions

1. Based on the development law of tunnel soil layer arching and considering soil arching effect influence, this paper proposes a triangular slip surface model for stratum development using limit equilibrium analysis methods, deriving tunnel earth pressure calculations considering expanding arch effect.

2. Based on the tunnel earth pressure calculation method established in this

paper, the influences of slip surface cohesion reduction coefficient λ, slip surface friction angle δ, and slip surface camber angle on calculated earth pressure are analyzed. Smaller cohesion reduction coefficients result in greater calculated tunnel earth pressure. Smaller slip surface friction angles yield greater calculated earth pressure, while larger slip surface camber angles produce smaller calculated earth pressure. With increasing depth, earth pressure first increases and then decreases.

3. Limit equilibrium analysis of earth pressure shows that with increasing tunnel burial depth, calculated earth pressure first increases and then decreases. Through comparative analysis of several limit equilibrium earth pressure calculation theories, selecting the rock-soil mass friction angle for slip surface friction angle and appropriate camber angles yields reasonable results. The cohesion reduction coefficient plays a decisive role in earth pressure calculation. Selecting a cohesion correction coefficient of λ=0.2 produces earth pressure calculations similar to other theoretical methods, demonstrating stronger applicability.

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