Research on Influence and Control of Unified Strength Theory of Geotechnical Materials on Deformation of Operating Metro Tunnels

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Abstract. The difficulty in controlling large deformation of subway tunnels has always been a difficulty during construction and later operation, especially after the tunnel is excavated, a loose circle is formed around the tunnel. If the initial support strength of the tunnel cannot effectively resist the deformation of surrounding rocks, then Subway tunnels will continue to deform after excavation. If this kind of continuous deformation cannot be effectively controlled, the deformation of the tunnel will exceed the original designed deformation, and the large deformation of the tunnel will bring huge hidden dangers to the operation of the subway. The initial support technology is essential to quickly and effectively suppress the continuous deformation of the tunnel. Based on the unified strength theory, this paper studies the deformation mechanism and laws of the tunnel, and discusses several feasible control methods.

Keywords: Geotechnical; strength theory; subway tunnel; deformation control.

1. Introduction
Geotechnical materials such as soil, rock, and concrete are the most widely used engineering materials in civil engineering and hydraulic engineering, and usually work under three-dimensional stress [1]. Deformation and strength characteristics of geotechnical materials are the basic problems in engineering structure design and analysis. Materials the strength of the material reflects the bearing capacity of the material, which is usually expressed by the ultimate load or ultimate deformation, that is, the reflection of the mechanical properties of the material under a certain failure criterion. The strength theory studies the failure law of the material under complex stress conditions, and the material is explained by the analysis model Coulomb expressed the shear strength of the soil as a function of the normal stress on the sliding surface according to the test results of sand. Coulomb's strength theory was proposed, which opened the prelude to the strength theory research [2]. The strength theory proposition attracts Researchers in many different fields have achieved fruitful research results and put forward hundreds of strength theories or guidelines [3].

The physical model of material strength is based on a certain point of view of material failure, forming a mechanical analysis model, and then obtaining a mathematical expression that describes the law of material strength, often called strength theory [4]. Material parameters in strength theory generally have clear physical meanings. For example, the Coulomb strength theory considers the shear...
strength on the sliding surface as a function of the normal stress on the surface, Mohr considers that the maximum shear stress acting surface is the sliding surface, and simplifies the Coulomb strength theory to a linear relationship between large principal stresses and small principals. The stress state on the sliding surface is expressed as a series of common tangent lines of stress circles [5]. The famous Mohr-Coulomb strength theory is proposed. The strength parameter, namely the internal friction angle, is now used to evaluate the shear resistance of geotechnical materials. Various strength models are devoted to the determination of the sliding surface. The strength models that have been established are given under the action, such as the maximum shear stress surface and the maximum shear stress ratio. With reference to the determination method of octahedral plane and SMP plane, the author puts forward the characteristic stress $\sigma_\theta^\beta$, Each material corresponds to a specific material parameter $\beta$, The octahedral plane under the action of $\sigma_\theta^\beta$ is considered to be the sliding surface of the material, and a nonlinear unified strength model of geotechnical materials is established. The model can better reflect the nonlinear strength characteristics of many types of geotechnical materials [6].

At present in the construction of large-scale subway tunnels in China, the problems of operation and maintenance of weak surrounding rock tunnels have always troubled the majority of tunnel builders. Weak surrounding rock tunnels are usually characterized by large deformation of the surrounding rock and even safety accidents such as collapse [7]. The main reasons for these problems are insufficient understanding of the deformation mechanism and development and evolution laws of the surrounding rock of the tunnel, especially the weak surrounding rock. Aiming at this series of problems, this paper makes a related research on tunnel deformation and control based on the unified strength theory [8]. The elastic-brittle-plastic calculation of the tunnel resistance coefficient was carried out. The deformation factors of the tunnel were analyzed and several improved control methods were provided [9].

2. Nonlinear unified strength model
The sliding surface of the Mises strength theory is an octahedron, and it is believed that the failure of the material is controlled by the shear stress on the sliding surface [10]. The Drucker--Prager strength theory develops the Mises strength theory, which considers the effect of hydrostatic pressure on the shear strength of the material. Still octahedral, as shown in Figure 1, the shear strength is considered to be a linear function of the normal stress on the sliding surface, which can be expressed as:

$$Q = mp + D$$  \hspace{1cm} (1)

Where $q$ is the generalized shear stress and $p$ is the average stress (or hydrostatic pressure). The expressions are:

$$q = \frac{\sqrt{2}}{2} \sqrt{\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_1\right)^2}$$  \hspace{1cm} (2)

$$p = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$$  \hspace{1cm} (3)

$M$ and $D$ are strength parameters, where $D$ is the shear strength when the average stress is zero; $M$ is a reflection of the friction characteristics of the material, and the internal friction angle $\varphi_c$ under triaxial compression can be expressed as:

$$M = \frac{6 \sin \varphi_c}{3 - \sin \varphi_c}$$  \hspace{1cm} (4)
2.1. Physical meaning and determination method of strength criterion parameters

The generalized nonlinear unified strength theory includes the strength, brittleness, and shear failure parameters of the rock, so it can well describe the basic properties of the rock [11]. The three parameters $\sigma_c$, $m$, $\beta$ in the strength criterion and the generalized Hoek-Brown strength criterion Parameters are consistent. Using the form of $\frac{\tau}{\sigma_c}$ to express the generalized Hoek-Brown strength criterion is:

$$\frac{\tau}{\sigma_c} = \frac{\cos \phi}{2(1 + \frac{\sin \phi}{\beta}) \frac{m}{\sigma_c}(\frac{\sigma}{\sigma_c} + 1)^\beta}$$  \hspace{1cm} (5)

The physical meaning of the parameter $\beta$ is its effect on the shear strength of the rock, which essentially increases the dilatancy angle of the rock and reflects the dilatancy characteristics of the rock under shear failure. When each parameter takes different values, the generalized nonlinear unified strength theory can degenerate into various strength criteria, as shown in Figure 2.

![Figure 1. Octahedron sliding surface](image)

![Figure 2. The relationship between generalized nonlinear unified strength theory and other strength theories](image)

2.2. Elastic-brittle-plastic calculation of resistance coefficient of surrounding rock based on nonlinear unified strength theory

The resistance coefficient of the surrounding rock is defined based on the Winkler foundation beam model (Thedbed-beam.modem.BBM), and is widely used by engineers in the design of the load structure method of tunnel linings. In this model, the resistance coefficient of the surrounding rock is an indispensable parameter for evaluating the self-bearing capacity of the surrounding rock, and in the
calculation of the internal force of the lining, the value of the resistance coefficient of the surrounding rock is very important. Due to the high cost of field tests and the long period of time, it is difficult to determine the value of the resistance coefficient of surrounding rocks based on previous engineering experience. It is often determined by checking specifications, even when the level of rock or soil or surrounding rock is a certain type. The range of resistance coefficient of surrounding rocks is also very wide, and it is difficult for engineers to take values based on engineering experience. The study found that the value of the surrounding rock resistance coefficient has a significant effect on the internal force of the lining. Therefore, accurately determining the value of the surrounding rock resistance coefficient is of great significance for describing the interaction between the surrounding rock and the supporting structure. However, under different stress conditions, the rock mass will appear elastic, brittle and plastic. Considering the plastic state of the rock mass can effectively improve the self-bearing capacity of the surrounding rock and reduce the engineering cost. If the rock mass has brittle nature, when the stress reaches the peak strength of the surrounding rock, the strength of the rock mass will suddenly decrease, such as a sudden decrease in cohesion and a decrease in self-bearing capacity. The plastic state of the surrounding rock can effectively improve the self-bearing capacity of the rock mass and reduce the engineering cost. When analyzing the plastic properties of the rock mass, it is very important to choose a reasonable strength criterion.

Researchers at home and abroad have carried out hydrostatic pressure effect tests on clay, rockfill, fine-grained sandstone, granite and other materials, and determined the material parameters based on the test results. Because the clay particles are difficult to break, the failure of the material is mainly caused by the displacement of the soil particles, which is manifested as the shear stress ratio failure. With the increase of hydrostatic pressure, the shear strength of clay basically shows a trend of linear increase. The other three materials have larger particles and stronger heterogeneity, which are more likely to be broken than clay particles. The destruction of the particles and the displacement between the particles eventually lead to the destruction of the material, which is mainly based on the shear stress ratio. The shear strength of the material increases slowly with the hydrostatic pressure, and the strength line exhibits a significant nonlinear characteristic. Therefore, the hydrostatic pressure sensitivity of clay is high, and the hydrostatic pressure effect parameter $n$ is large. The rockfill and fine-grained sandstone have the same hydrostatic pressure sensitivity, and the friction angle under triaxial compression obtained under the same reference stress is the same. Although the hydrostatic pressure sensitivity of granite is the same as that of rockfill and fine-grained sandstone, the Different, so the obtained friction angle during triaxial compression is different.

3. Tunnel deformation mechanism
Surrounding rock deformation refers to the deformation of the rock mass around the tunnel, and the rock masses are extremely complex geological bodies. The main aspects of their complexity are shown in Figure 3.

![Figure 3. Classification of rock and soil deformation mechanisms](image-url)
(1) The complexity of material components: The material components that make up the rock and soil, that is, the mineral components are very complex. There are very hard diamonds, quartz, and so on, as well as very weak talc, gypsum, and calcite.

(2) Structural discontinuities: Faults, joints, bedding, unconformities and other geological structures often appear in rock masses, making the surrounding rock structure discontinuous.

(3) Inhomogeneity of material distribution: The density distribution of the rock mass in which the tunnel is located is uneven, and soft rock layers and soil-rock mixture often occur.

(4) Material instability: Surrounding rocks are often affected by the surrounding environment and instability occurs. For example, phyllite and shale often soften after encountering water, frozen soil changes due to the influence of climate, and expansive surrounding rocks encounter Volume expansion after water etc.

(5) The complexity of the existing environment: The surrounding rocks are all in a certain geological environment, such as groundwater, ground stress, ground temperature, etc. These geological environments have a large or small impact on the deformation of the surrounding rocks. The complexity of the surrounding rock itself will inevitably lead to the complexity of the surrounding rock deformation, which will cause various deformation mechanisms to appear in the surrounding rock.

The deformation of the surrounding rock of the tunnel is the result and external manifestation of the stress adjustment of the surrounding rock, and the adjustment of the surrounding rock stress is a three-dimensional dynamic process caused by the excavation of the palm face. Therefore, the deformation of the tunnel surrounding rock is a space; and a time variable. For hard and brittle Grade 1 and 2 surrounding rocks, the stress adjustment is completed at the moment of excavation, and the deformation of the surrounding rock is also terminated at the moment of excavation. The deformation of the surrounding rock is mainly elastic and plastic. At this time, the deformation of the surrounding rock is only a function of space and has nothing to do with time, that is, the deformation of the surrounding rock does not increase with time. However, for grade-to-grade surrounding rocks, the adjustment of stress cannot be completed in an instant. Especially for weak surrounding rocks of grades 6 and 6, the time for stress adjustment is often long. At this time, the deformation of the surrounding rock is a function of space and time.

4. Tunnel deformation control method
The purpose of tunnel surrounding rock deformation control is to control the deformation within the allowable range during the excavation process and support construction, and to ensure the long-term stability of the tunnel structure system. Excavation is a process of releasing stress. Different excavation methods have different processes and degrees of stress release. Support is a method of stress control. Similarly, the process and degree of stress control of different support methods are different.

4.1. Control method of rigid structure
The rigid structure control concept is to control the deformation of the surrounding rock and strengthen the rigidity and strength of the supporting structure. That is, the rigid support is used to control the deformation of the surrounding rock as early as possible. This method will design the initial support very strong. The secondary lining is applied as early as possible to resist deformation. The rigid structure control concept usually adopts two measures to strengthen the rigidity of the support and lining structure and improve the self-supporting ability of the surrounding rock to control the deformation of the surrounding rock.

(1) Strengthen the stiffness of support and lining structures
This measure is to use long anchor rods, heavy steel frames and large-thickness sprayed concrete support to control ground subsidence or tunnel deformation under conditions of shallow buried ground, low ground weight or surrounding rock pressure, and soft ground.

(2) Improve the self-supporting ability of surrounding rocks
Under the conditions of shallow buried ground, low ground weight or surrounding rock pressure, soft ground, etc., in order to reduce ground subsidence or tunnel deformation, efforts are made to improve
and strengthen the ground. Deep-hole large-scale advanced grouting or horizontal rotary jetting with large rigidity or large pipe shed advanced support, palm-face advanced long-anchor pipe reinforcement is adopted to improve the strength and stiffness of surrounding rocks. The above method is suitable for structures with ground surface, which has certain requirements for settlement control, and does not have the conditions to take engineering measures on the ground. In this case, only strengthened engineering measures are taken in the cave. The second method is applicable to the tunnel entrance section or shallow buried tunnel section, where there are structures nearby, which have higher requirements for tunnel settlement or deformation, the ground surface is open, and the construction period is relatively tight. In this case, a large area can be used. At the same time, stratum reinforcement and improvement were carried out. The second method is simple in process, reliable in quality, fast in construction speed, but high in investment.

4.2. Flexible control methods

The concept of flexible structure control is to reduce the load acting on the support, simplify the support structure, and adopt the method of releasing deformation, that is, by increasing the amount of reserved deformation, the surrounding rock stress is fully released, and then the support structure is applied. Flexible structure control concepts often adopt measures such as multiple supports, retractable supports, and comprehensive control in stages to control surrounding rock deformation.

(1) Retractable support

This measure also needs to reserve sufficient allowable deformation and secondary support space. Under the support of advanced anchor pipes or anchor rods, a support system such as a retractable anchor rod and a retractable steel frame is erected in time after tunnel excavation, allowing for greater deformation and release of surrounding rock pressure to reduce the load on the supporting structure. The shrinkable support structure has complicated technology, high technical requirements and a long construction period.

(2) Comprehensive control in stages

Preset is sufficient to reserve space for deformation and secondary support. Under the support of advanced anchor pipes or staggered rods, short and medium system anchors, steel frames, and shotcrete support are set after excavation to restrict the initial deformation of surrounding rocks: Then, at a position about 3.0D from the back of the palm face, a system long anchor rod is set to reinforce the surrounding rock, and if necessary, net sprayed concrete or steel frame sprayed concrete is used for reinforcement. Due to the insufficient rigidity of the prior support, this method can only restrain the initial deformation of the surrounding rock and it is difficult to control the deformation. The long anchor bolt reinforcement method is used to increase the support stiffness in stages to control the deformation and stabilize the tunnel. This method requires a small space for support and reinforcement. The application of reinforcement anchors behind the working surface is beneficial to the construction of long anchors, the number and quality of anchors, and the parallel operation of construction.

5. Conclusion

After excavation of a soft rock tunnel, a loose circle is formed around it. The way in which the broken rock mass within the range of the loose circle transmits the ground stress changes greatly. When the initial support strength of the tunnel cannot resist the expansion force of the surrounding rock of the loose circle at this time, the loose circle around the tunnel will continue to expand, so that the soft rock tunnel will continue to deform. Based on the unified strength theory, the elastic-brittle-plastic calculation of the tunnel resistance coefficient is analyzed in this paper. The deformation factors of the tunnel are analyzed and the use of rigid structures and flexible control methods is proposed to improve the safety and stability of subway operations.

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