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Analysis of the failure mechanism of tunnels constructed in heavy clay soils

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Abstract: *Heavy cohesive soil tunnel plays an important role in underground engineering, but its failure mechanism has always been one of the focuses of research. Cohesive soil means clay (fine grained soil), or soil with a high clay content, which has cohesive strength. Cohesive soil does not crumble, can be excavated with vertical side slopes, and is plastic when moist. Cohesive soil is hard to break up when dry, and exhibits significant cohesion when submerged. This paper aims to analyze the failure mechanism of heavy cohesive soil tunnel. This could be generally attributed to the reduced mechanical and deformation characteristics of the soil- like ground, which in turn could lead to a failure event via excessive deformations, loosening of their texture, excessive exerted stresses and structural instability. The definition and physical and mechanical properties of heavy clayey soil were summarized, which paved the way for the following contents. Then, the definition of tunnel damage and different types of tunnel damage are introduced, which provides basic concepts for understanding heavy cohesive soil tunnel failure. In the part of the research on the failure mechanism of the heavy cohesive soil tunnel, the influence of groundwater on the heavy cohesive soil and the tunnel failure caused by the change of ground stress are discussed. Through the in-depth analysis of these factors, we can better understand the failure mechanism of heavy cohesive soil tunnel, and provide scientific basis and technical support for related projects.*
Key Words: *Heavy cohesive soil tunnel; Ground stress variation; Land surface settlement; Tunnel deformation; Failure mechanism.*

1. INTRODUCTION :

1.1 Research Background

As an important transportation and infrastructure construction project, tunnel engineering plays a vital role in the process of urbanization. However, tunnel projects in many areas face the challenge of focusing on sticky soil layers, which poses a potential threat to the stability and safety of tunnels.[1]

Heavy cohesive soil has the characteristics of high water content, high sand content and low pore ratio, and it shows great deformation ability when it is regulated by stress. These characteristics make heavy cohesive soil more prone to liquefaction, subsidence and side rock pressure increase during tunnel excavation and operation. Therefore, it is of great significance to study the failure mechanism of heavy cohesive soil tunnel to improve the safety and reliability of tunnel engineering. Through the study of the influence of groundwater on soil, the damage caused by the change of ground stress and the physical and engineering characteristics of soil, the internal mechanism can be revealed, which can provide scientific basis for the design and construction of tunnel engineering, reduce the engineering risk and improve the engineering quality.

1.2 RESEARCH PURPOSE AND SIGNIFICANCE

1.2.1 Research purpose

The purpose of this study is to deeply analyze and explore the failure mechanism of heavy cohesive soil tunnel, so as to improve the understanding of tunnel engineering under this special soil environment. The research objectives are as follows:

Study the influence of groundwater on the heavy cohesive soil: Analyze the influence mechanism of groundwater on the saturation, water holding capacity and permeability of the heavy cohesive soil, and explore its influence on the strength, stability and deformation characteristics of the soil.[2]

Analysis of tunnel failure caused by the change of ground stress: By analyzing the change of ground stress distribution during tunnel excavation and construction, the influence on the mechanical behavior and failure characteristics of heavy cohesive soil, including soil subsidence and lateral rock pressure, is studied.

Study the physical and engineering properties of heavy cohesive soil: study the physical and engineering properties of heavy cohesive soil, including its high water content, high sand content and low pore ratio, as well as problems such as plasticity, loss and collapse, so as to provide a basis for understanding the failure mechanism of heavy cohesive soil tunnels.

1.2.2 Research significance

The significance of studying the failure mechanism of heavy cohesive soil tunnel is mainly reflected in the following aspects:[3]

Improve the safety and reliability of tunnel engineering. The heavy viscous soil layer poses a potential threat to the safety of tunnel engineering, which is easy to cause liquefaction, settlement, and the increase of side rock pressure. Through in-depth study of the failure mechanism of heavy cohesive soil tunnel, its internal law and evolution process can be better understood, and scientific basis can be provided for engineering design, construction and monitoring, so as to effectively reduce the occurrence of tunnel damage and accidents, and improve the safety and reliability of the project.

Optimize the design, construction and maintenance of tunnel projects. The study of the failure mechanism of heavy viscous soil layer provides important guidance for the design, construction and maintenance of tunnel engineering. Through in-depth understanding of the influence of groundwater on the heavy cohesive soil, the damage caused by the change of ground stress and the mechanism of the physical and engineering characteristics of the soil, reasonable prevention and control measures and management strategies can be formulated, scientific planning of the construction sequence, control of the groundwater level and pressure, and strengthen the discharge of groundwater, so as to improve the quality and efficiency of the tunnel project.

Promote academic research and progress in the field of civil engineering. The study of heavy cohesive soil tunnel failure mechanism involves the intersection and fusion of soil dynamics, geotechnical engineering, groundwater engineering, tunnel engineering and other disciplines. In the process of in-depth study, we can learn from and develop various testing, simulation and analysis methods, and enrich and improve the geotechnical theory and engineering practice experience. At the same time, it will promote academic exchanges and cooperation in related disciplines and promote the further development and progress of disciplines.

2. RELEVANT OVERVIEW OF HEAVY COHESIVE SOIL :

2.1 Definition of heavy cohesive soil

Heavy cohesive soil is a kind of soil with high cohesiveness and plastic characteristics, which refers to the soil with little sand content, fine particles, slow water seepage rate, good water retention performance and poor ventilation performance. Heavy clay soils are soils with plasticity index greater than 10 and particle content greater than 0.075mm not exceeding 50% of the total volume, including clayy sand, sand with low liquid limit clay, sand with high liquid limit clay, sand with high liquid limit clay and high liquid limit clay. This type of soil generally refers to the physical clay 45%, fine texture (viscosity). Heavy cohesive soils usually appear in a fluid, hard or plastic state, with a high degree of cohesion and cohesiveness, resulting in greater shear strength and plasticity. Clayey soil is also called clay soil, as shown below. The main components of heavy clayey soil are clay particles, including clay and clay particles. Clay is a kind of fine granular mineral soil, with high plasticity and viscosity, easy to absorb water and form a colloidal substance. Clay particles are fine particles with adhesive force and plasticity, which can form a viscose substance by absorbing water.

Heavy cohesive soil has a large liquid-plastic index, which indicates that it has high plasticity and fluidity. It has a high water content, can appear like a fluid, and has a strong water absorption in the pores. The physical properties of heavy cohesive soils also include low permeability and low permeability, resulting in slower migration of water within them. In addition, heavy cohesive soil also has high cohesion and cohesiveness, which makes it have greater shear strength and plasticity.

Figure 2-1 Heavy cohesive soil

2.2 PHYSICAL AND MECHANICAL PROPERTIES OF HEAVY COHESIVE SOIL

Heavy clay has unique physical and mechanical properties, including compactness, mass water content, pore structure and permeability, and mechanical properties mainly include cohesion, cohesion, shear strength and plasticity.[4]

The physical characteristics of heavy clay include compactness, mass water content, pore structure and permeability. Compactness refers to the tightness of soil particles and is usually expressed as the mass of soil particles per unit volume. Mass water content refers to the ratio of the water mass contained in the soil to the dry mass of the soil, reflecting the amount of soil water content. Pore structure refers to the distribution and size characteristics of various pores in soil, including micro-pores, mesoporous pores and macropores. Permeability refers to the ability of soil to penetrate water and is affected by factors such as soil particle size, particle shape and pore connectivity.

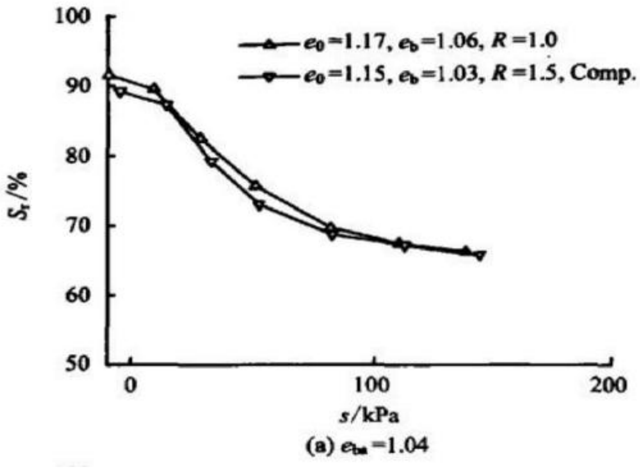

Figure 2-2 Physical analysis of heavy cohesive soil[5]

The mechanical properties of heavy clay include cohesiveness, cohesiveness, shear strength and plasticity. Cohesion refers to the attractive force generated by the surface of soil particles, and is often related to the bonding and adsorption force of clay particles. Cohesion refers to the bonding force inside the soil particles, which is mainly formed by the joint action of adsorption force and surface tension. Shear strength refers to the resistance of soil to shear stress and is usually described by the shear strength parameter. Plasticity refers to the deformation characteristics of heavy cohesive soil, including plastic limit and plastic index.

Heavy clay has high cohesion and cohesiveness, which makes it have great shear strength and plasticity. Its physical and mechanical properties are affected by many factors, such as particle size distribution, composition, water content and pore structure. Therefore, the specific physical and mechanical properties need to be measured and analyzed according to the actual situation.

3. BASIC CONCEPTS OF TUNNEL FAILURE MECHANISM :

3.1 Characteristics of tunnel damage

Surface cracking and displacement: Tunnel damage is often manifested by surface cracking and displacement. In the heavy cohesive soil tunnel, the soil is prone to cracking and displacement due to the action of groundwater, ground stress and other factors. These cracks and displacements not only affect the structural integrity of the tunnel, but can also lead to problems such as water seepage and collapse inside the tunnel, thus posing a threat to the safe operation of the tunnel.

Deformation and variation of geological body: Tunnel damage also shows the deformation and variation of geological body. The geological body around the heavy cohesive soil tunnel is often affected by groundwater and ground stress, and may undergo deformation and variation such as compression, expansion and sliding. The deformation and variation of these geological bodies will directly affect the stability and safety of tunnel structure, which needs to be controlled and managed by effective support measures and monitoring means.

Internal water seepage and liquefaction phenomenon: Another characteristic of heavy cohesive soil tunnel damage is internal water seepage and liquefaction phenomenon. Due to the characteristics of soil and the influence of groundwater, water seepage often exists in tunnel, especially under the change of external environment such as earthquake, which may lead to the liquefaction of soil and seriously endanger the safety of tunnel. Therefore, it is necessary to take effective anti-seepage and anti-liquefaction measures to ensure the stability and safety of the tunnel.

3.2 Basic modes and types of tunnel failure

Tunnel failure refers to the process of tunnel structure failure or failure due to various reasons during construction or use. There are many basic modes and types of tunnel failure, mainly the following three.[7]

Soil cover instability: This failure mode mainly occurs in shallow buried tunnels, that is, the soil cover thickness is less than the tunnel diameter. When the overlying pressure changes due to construction or operation, if the overlying pressure exceeds the bearing capacity of the soil, it will cause the instability and failure of the tunnel top or side wall. The common types of instability failure include roof subsidence, roof spalling, side wall collapse, etc. As shown below.

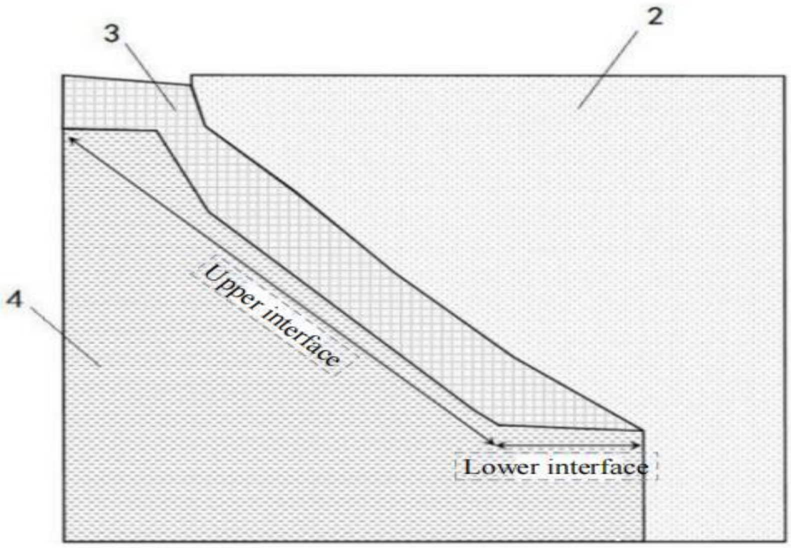

Figure 3-1 soil instability type

Rock failure type: This failure mode mainly occurs in the roadway in the lithologic stratum. Due to the limited strength and stability of surrounding rock, the tunnel is affected by vibration, ground stress change, water pressure and other factors during construction or use, and the rock formation may be damaged in the form of rupture, spalling, sliding and so on. The common rock failure types are rock cracking, rock sliding, rock collapse and so on. As shown below.

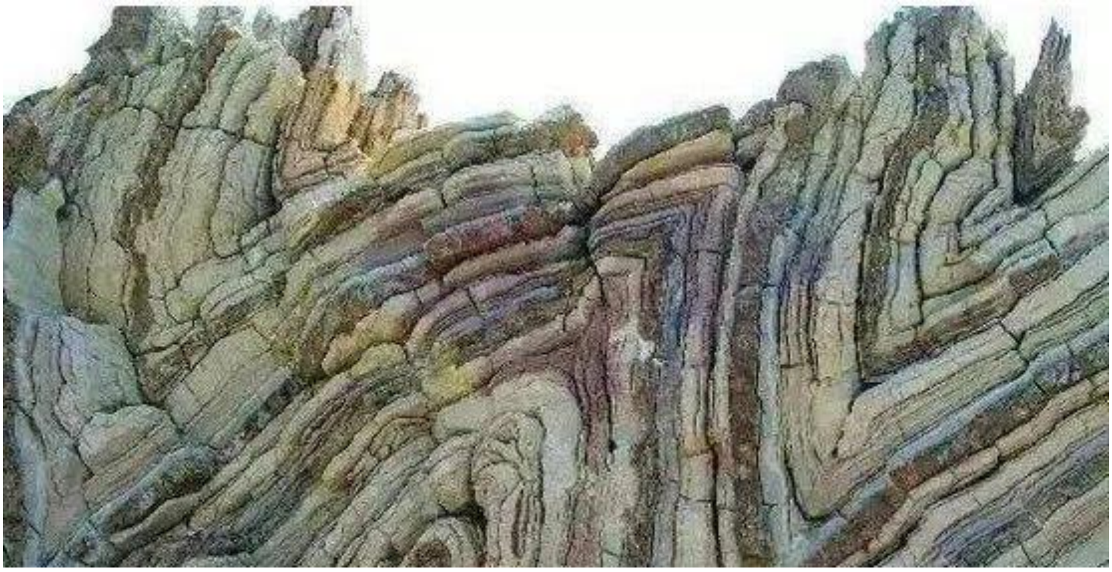

Figure 3-2 Rock damage type

Groundwater damage type: groundwater is one of the important factors that cause tunnel damage. When the tunnel passes through the groundwater aquifer, the change of groundwater pressure and seepage will occur, which may lead to the instability of the soil saturated state, resulting in liquefaction, debris flow and other disasters. The common types of groundwater damage include tunnel water gushing, karst cave collapse caused by groundwater seepage, and debris flow erosion. As shown below.

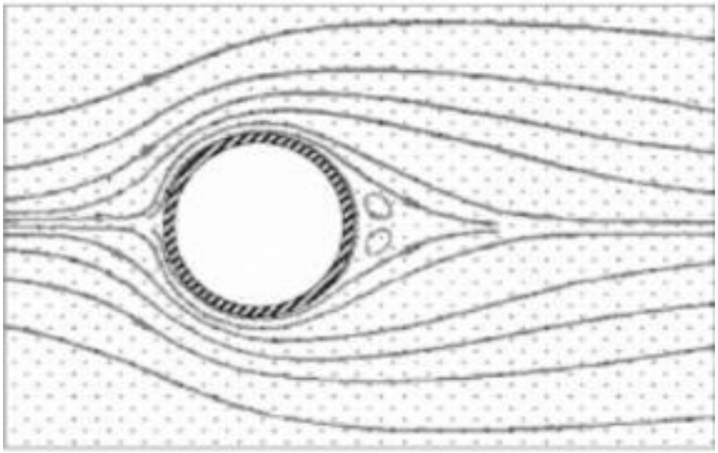

Figure 3-3 Groundwater damage type

3.3 Characteristics of heavy cohesive soil tunnel failure mechanism

Complexity and multi-factor influence: The failure mechanism of heavy cohesive soil tunnel is extremely complex, involving the interaction of multiple factors. First of all, geological conditions have an important effect on the properties and behavior of heavy cohesive soil, including soil composition, particle structure, water content and so on. Secondly, the shear force, deformation variable, underground flow and other factors during tunnel excavation and construction also have obvious influence on the heavy cohesive soil. Therefore, the failure mechanism of heavy cohesive soil tunnel is not only restricted by geological factors, but also by construction technology and hydrogeological conditions.

Plasticity and gradualism: Heavy clay has high plasticity and deformability, and is very sensitive to stress changes. In the process of tunnel construction and operation, the deformation and stress distribution of soil will change, and with the action of stress, the heavy cohesive soil may gradually produce plastic deformation and failure. The failure process is often gradual and may go through multiple stages, and the deformation and failure of soil mass may gradually intensify with the passage of time.

Influence of high water content and groundwater: Heavy cohesive soil is characterized by high water content and large pore water pressure. Groundwater plays an important role in the failure mechanism of heavy cohesive soil. When the ground water level rises or there is a high water pressure, the strength and stability of the soil will decrease as the heavy cohesive soil becomes saturated and the pore water pressure increases. In addition, groundwater may also cause seepage and dissolution of soil mass, further increasing the risk of tunnel damage.

4. FAILURE MECHANISM OF HEAVY COHESIVE SOIL TUNNEL :

4.1 Influence of groundwater on heavy cohesive soil

The influence of groundwater on the heavy cohesive soil is mainly manifested as the increase of seepage, soil saturation and liquefaction, and surface settlement and subsidence. In tunnel construction, when the ground water level is higher than the buried depth of the tunnel, the groundwater will flow through the pores of the soil, resulting in an increase in

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the permeability of the soil. Increased seepage changes the physical properties of soil. One of the important parameters is the permeability coefficient, which is used to describe the permeability of soil. Penetration test and wall seepage test are commonly used to measure the permeability coefficient.

The permeability coefficient can be calculated by the following formula:

k = Q/(A*ΔH*L)

Where, k represents the soil permeability coefficient, the unit is m/s;

Q represents the amount of water passing through the soil per unit time, in cubic meters per second;

A represents the cross-sectional area of the soil seepage section, the unit is square meters;

ΔH indicates the seepage distance in meters;

L represents the penetration time, expressed in seconds.

The presence of underground water may increase the permeability coefficient, thus affecting the permeability of soil around the tunnel, as shown in the figure below. If the groundwater flow is large, the soil permeability is enhanced, which may weaken the shear strength of the soil and increase the deformation ability of the soil, thus affecting the stability of the tunnel.[7]

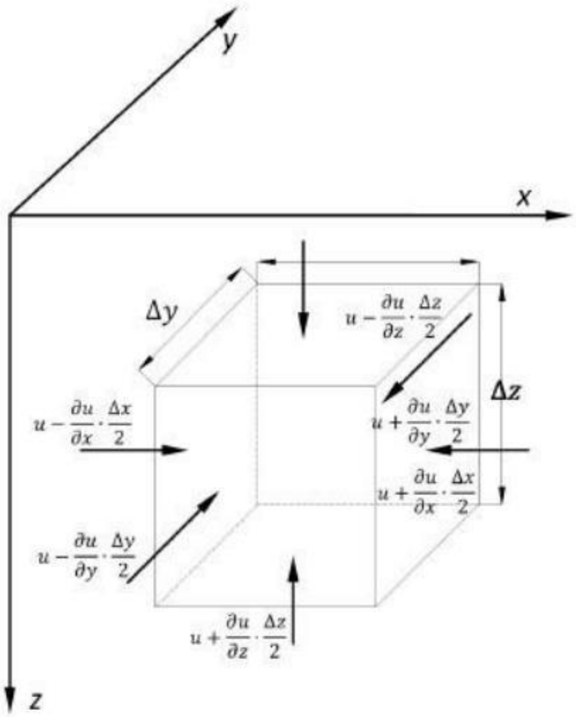

Figure 4-1 State of pore water pressure at a point in soil

In addition, the existence of groundwater may also lead to soil saturation and liquefaction problems. The strength of saturated soil is usually low, and liquefaction makes the soil lose its resistance, resulting in a fluid state, which is prone to settlement, sideslip, collapse and other damage phenomena. The calculation formula of soil liquefaction is as follows:

CSR = (CRR/SBT)/(Δu/u0)

Among them, CSR represents the static anti-liquefaction safety factor;

CRR represents shear volatility in the range of 0.1-0.3, expressed in g;

SBT means moisture content to physical property index, generally 1.0;

Δu represents the increase of pore water pressure during the maximum effective drainage of ground motion, in kPa;

u0 represents static pore water pressure in kPa.

The influence of groundwater on heavy cohesive soil is mainly manifested as seepage increase, soil saturation and liquefaction, and surface settlement and subsidence. The calculation of seepage increase can be made using the permeability coefficient formula, while the calculation of liquefaction can be made using the static anti-liquefaction safety factor formula. These formulas can help engineers to evaluate the impact of groundwater on the heavy cohesive soil project, so as to take appropriate control and reinforcement measures to ensure the safety of the project.

4.2 Tunnel damage caused by changes in ground stress

The heavy cohesive soil tunnel is prone to failure under the influence of ground stress change, and the main mechanisms include ground stress redistribution, surface settlement and tunnel deformation. In the process of tunnel excavation, the distribution of ground stress will change, which will cause the damage of heavy cohesive soil tunnel. It mainly includes the following aspects:

Redistribution of ground stress: Tunnel excavation will lead to the cutting and hollowing of surrounding rock, resulting in redistribution of ground stress. In the soil around the excavation, some of the ground stress is removed, while other parts are in a state of increased stress. This redistribution of ground stress will cause the original equilibrium soil to lose stability and cause local or whole damage.

Land subsidence: Changes in ground stress caused by tunnel excavation can cause land subsidence. When the underground cavity is formed or the soil mass collapses, the surface subsidence will occur. The ground subsidence affects the surrounding buildings and underground pipelines, and may cause the cumulative effect of ground subsidence.

Tunnel deformation: Changes in ground stress can cause deformation of heavy cohesive soil tunnels. When the local stress is changed, the soil will undergo elastic and plastic deformation. The change of ground stress caused by excavation may lead to tunnel compression, contraction or deformation, which may lead to the damage of tunnel structure.

The influence of ground stress variation on heavy cohesive soil tunnels can be evaluated by calculating stress distribution, deformation and settlement. The calculation formula is as follows:

Calculation formula of land surface settlement:

Delta S = gamma ΔH

Among them, ΔS represents the land surface settlement, the unit is meter;

Gamma represents the unit weight of the heavy cohesive soil, in kN/m3;

ΔH indicates the change in thickness of the soil mass in meters.

By calculating the surface settlement, the impact of tunnel excavation on the surface can be evaluated. It should be noted that the change of ground stress involves the elastic and plastic deformation of soil, and the specific calculation method needs to be comprehensively analyzed according to the specific engineering conditions and soil parameters.

5. CONCLUSION:

Through this study, we find that groundwater is one of the important factors of heavy cohesive soil tunnel failure. The infiltration of groundwater will change the mechanical properties of the soil and lead to the decline of the stability of the tunnel structure. Therefore, in the process of design and construction, it is necessary to fully consider the impact of groundwater and take effective drainage measures to ensure the safe operation of the tunnel.

The underground construction and surface load change may cause the change of ground stress, which will affect the heavy cohesive soil tunnel. Our research shows that the change of ground stress may lead to the deformation and destruction of tunnel structures, especially under the external environment changes such as earthquakes. Therefore, in tunnel design and construction, it is necessary to consider the change of underground stress and take appropriate supporting measures and monitoring means to cope with the possible influence of ground stress change on tunnel.

With the development of underground engineering and the progress of technology, our understanding of the failure mechanism of heavy cohesive soil tunnel needs to be further improved. Future research can be carried out from the following aspects: in-depth study of the interaction mechanism between groundwater and heavy cohesive soil tunnels to explore more effective groundwater management and control methods; Strengthen the research on the influence mechanism of ground stress changes on tunnel stability, and put forward more reliable earthquake response strategies and underground engineering design standards. At the same time, in engineering practice, the latest research results should be combined with the continuous improvement of tunnel design, construction and monitoring technology to ensure the safe operation of heavy clay tunnel.

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