

Safety Analysis of Tunnel Construction under Complex Geological Conditions

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ABSTRACT

This paper primarily explores the safety issues faced during tunnel construction under complex geological conditions and proposes a series of innovative safety measures. The article starts by examining the characteristics and challenges of tunnel engineering in such conditions, discussing in detail potential safety hazards encountered during construction, such as rock mass stability, groundwater control, blasting and excavation techniques, as well as support and lining schemes. For each of these challenges, corresponding improvement measures and technological innovations are suggested. It is hoped that this research will contribute to the advancement of tunnel engineering technology, enhance construction safety, and promote more sustainable development goals.

KEYWORDS

geological conditions; tunnel construction; construction safety

1 Introduction

With the rapid development of modern society, the importance of infrastructure construction has become increasingly prominent. As a crucial component for connecting different regions and overcoming natural obstacles, tunnel engineering plays an indispensable role. However, as construction projects progress into more complex geological conditions, the difficulty and safety risks associated with them have also escalated. Complex geological conditions encompass adverse geological factors, such as alternating soft and hard rock layers, high-stress areas, and fault fracture zones, as well as environmental challenges like abundant groundwater and abnormal ground temperatures. These factors significantly affect the safety and efficiency of tunnel construction and place higher demands on engineering techniques. In light of these challenges, ensuring the safety of construction personnel, maintaining project quality, and minimizing the impact on the surrounding environment have become pressing issues to address.

2 Characteristics of Tunnel Engineering under Complex Geological Conditions

2.1 Complexity of Geological Structure

The first challenge in tunnel construction under complex geological conditions is the complexity of the geological structure. This complexity is mainly found in fault zones, folds, and other structural belts, where the rock mass is often fragmented and unstable. These areas are highly susceptible to collapse and deformation, increasing both the difficulty and risk of construction. The existence of geological structural belts leads to significant variations in surrounding rock properties, meaning that different engineering measures may be required at different locations along the tunnel^[1]. Furthermore, the discontinuity and variability of geological structures demand that the engineering team possess advanced expertise and technical skills to accurately assess geological conditions and adjust construction plans accordingly.

2.2 Frequent Groundwater Activity

Another prominent characteristic of tunnel construction under complex geological conditions is the frequent activity of groundwater. This is especially true in water-rich sand layers, karst regions, or areas with caves, where groundwater not only affects the stability of the excavation face but also potentially causes water influx, introducing great uncertainty into the construction process. The frequency and intensity of groundwater activity directly influence both the safety and progress of the project. In such situations, effective management and control of groundwater are critical to ensuring the smooth progress of construction. Groundwater can also soften the rock, further exacerbating the risk of surrounding rock instability.

2.3 Uneven Layered Rock Hardness

The characteristic of uneven hardness in the strata is particularly pronounced, with transitions between rocks of varying hardness placing special demands on excavation equipment and potentially leading to unstable excavation

speeds and increased wear on machinery. Under these conditions, the construction team must select appropriate excavation techniques and tools based on the specific characteristics of the strata to improve work efficiency and minimize equipment damage. Additionally, the uneven nature of the strata complicates the design of tunnel lining, requiring engineers to carefully consider the challenges posed by the differences in rock layers to design support structures that are both cost-effective and safe.

2.4 Random Distribution of Karst Caves

The presence of karst caves presents significant challenges for tunnel engineering due to their random distribution, making them difficult to predict. Caves can unexpectedly appear along the tunnel path, severely disrupting the normal construction process. These caves not only affect the direct excavation of the tunnel but also add complexity due to the internal structure of the caves (such as the size and connectivity of the voids), making them harder to manage. As a result, when encountering karst caves, the construction team typically needs to conduct detailed geological surveys and develop corresponding strategies based on the specific conditions to ensure both the quality of the project and the safety of personnel.

2.5 Rock Bursts and Large Deformations Caused by High Ground Stress

Construction in high ground stress areas faces the risk of rock bursts and large deformations. In such geological conditions, the release of internal stress within the surrounding rock is intense and can pose serious threats to construction safety. A rock burst is the sudden fracturing and ejection of rock under high stress, characterized by its abruptness and danger. Large deformations, on the other hand, occur when the surrounding rock slowly and persistently moves toward the tunnel space, subjecting the support structure to enormous pressure. To address these challenges, the construction team must employ advanced monitoring techniques to keep track of the surrounding rock conditions in real-time, as well as implement effective reinforcement measures to enhance rock stability and ensure the safe progression of the construction process.

3 Safety Issues in Tunnel Construction under Complex Geological Conditions

3.1 Rock Mass Stability

When constructing tunnels under complex geological conditions, rock mass stability is one of the key factors affecting the safety of the project. Rock type, structural features, and stress conditions all play significant roles in the stability of the rock mass. In some mountainous tunnel projects, construction teams frequently encounter collapse incidents due to the crossing of multiple layers of different types of rock, such as hard granite and weak shale. The complexity of the geological environment increases the difficulty of construction, especially in high-stress sections, where rock bursts can occur, posing significant safety risks to workers.

Additionally, the presence of fault zones and fractured belts greatly threatens tunnel stability. In these areas, the rock mass is often loose and lacks self-supporting capability, making it prone to local collapse or overall instability. In some real-world cases, even preliminary support measures have failed to completely prevent these issues. Fault zones not only delay construction progress but can also lead to severe safety incidents, such as equipment damage or casualties.

The heterogeneity of the rock mass is another important cause of instability. In certain cases, there are numerous cracks and cavities within the rock mass, which weaken its overall strength and make it more susceptible to external disturbances. For instance, during the construction of a diversion tunnel for a hydroelectric project, the construction team encountered numerous limestone layers with cracks, leading to frequent minor collapses, which severely threatened the safety of workers^[2].

3.2 Groundwater Issues

Groundwater activity presents a severe threat to tunnel construction, particularly in areas with rich hydrogeological conditions, where water inflow and mud outbursts are common. Water ingress can lead to flooding within the tunnel, disrupting normal operations and possibly causing surrounding rock to soften, increasing the risk of collapse. In several underground transportation tunnel projects in coastal cities, high groundwater levels and the permeable nature of the strata led to multiple water inflow incidents during construction, significantly affecting project timelines and increasing safety risks.

In extreme cases, the pressure from groundwater can be so high that it damages the tunnel lining structure or even causes overall tunnel instability. The chemical composition of the groundwater may also corrode metal components

inside the tunnel, further weakening structural integrity. Moreover, groundwater activity can impact the surrounding environment, potentially causing surface settlement, which poses a threat to nearby buildings and infrastructure. This settlement may also raise concerns among residents and contribute to social instability.

3.3 Blasting and Excavation Issues

As a critical aspect of tunnel construction, the safety of blasting operations directly influences the success or failure of the project. Improper blasting design can lead to further damage to surrounding rock, resulting in safety accidents. In mountainous tunnel projects, if the characteristics of the rock layers are not fully considered at the outset and excessive explosives are used, local rock collapse may occur, leading to casualties. The shockwaves from blasting can disturb the surrounding rock mass, potentially causing crack propagation and leading to further instability.

Under complex geological conditions, the unevenness and fragility of the rock layers make blasting operations particularly hazardous. For example, when tunneling through fault zones or weak rock layers, even minor blasting operations can trigger large-scale rock collapses. Blasting-induced flying debris can also cause direct harm to workers and damage equipment. Moreover, blasting operations have a negative impact on the surrounding environment, such as noise and air pollution.

3.4 Support and Lining Issues

Support and lining technologies play an irreplaceable role in ensuring the long-term stability and safety of tunnels. However, selecting the appropriate support scheme is challenging under complex geological conditions. For example, in tunnels crossing fault zones, where the rock mass is loose and lacks self-stabilizing capacity, traditional support methods often fall short. In such cases, even conventional support measures like steel arches and shotcrete may struggle to effectively control rock mass deformation.

As tunnel depth increases, surrounding rock pressure also escalates, placing higher demands on support structures. In deep-buried tunnel projects, excessive surrounding rock pressure can result in loads far exceeding the design limits of the support system, leading to deformation or even failure. This situation not only affects the overall stability of the tunnel but can also hinder subsequent construction activities.

The quality of the lining structure (such as cracks and leakage) cannot be overlooked, as these issues directly impact the tunnel's service life and safety. In certain cases, small cracks in the lining structure may gradually expand, eventually resulting in larger fissures and causing water leakage or other more severe problems.

4 Innovative Safety Measures for Tunnel Construction

4.1 Safety Measures for Rock Mass Stability

Ensuring rock mass stability hinges on the use of advanced monitoring technologies and effective reinforcement methods. Microseismic monitoring technology, an emerging geological monitoring tool, captures minute vibrations within the rock mass in real time. By analyzing the trends in these signals, it can predict potential rock mass instability risks. In large-scale mountain tunnel projects, microseismic monitoring systems can help warn construction teams of impending local collapses, thereby preventing major safety accidents. Additionally, laser scanning technology is widely applied to precisely measure changes in the surface morphology of rock masses, providing high-accuracy data for stability assessments.

Reinforcement techniques have also evolved, offering new solutions to enhance rock mass stability. Two commonly used reinforcement methods—rock bolts and grouting—have seen significant improvements in material selection and application technologies in recent years. New high-strength rock bolts offer superior tensile strength and excellent corrosion resistance, ensuring their structural integrity even in extreme environments. Grouting involves injecting specialized chemical grout to fill rock fissures, thereby enhancing the overall cohesion and stability of the rock mass.

4.2 New Strategies for Addressing Groundwater Issues

To tackle complex hydrogeological conditions, optimizing drainage system designs has become a key strategy in addressing groundwater issues. Modern drainage systems no longer rely solely on traditional gravity drainage methods but incorporate advanced technologies like vacuum suction and electroosmosis to create multi-level, multidimensional integrated drainage solutions. Construction teams should adopt intelligent drainage control systems, which dynamically adjust pump operation frequencies based on groundwater levels, maximizing drainage efficiency while minimizing energy consumption^[3].

Innovations in waterproofing technology have also significantly enhanced tunnel construction safety. High-performance waterproof membranes, known for their superior waterproofing capabilities and adaptability, have become an ideal solution for addressing groundwater seepage. Chemical grouting techniques involve injecting specific chemicals into the strata to form a stable water barrier, preventing groundwater from entering tunnel areas. During the construction of urban rail transit tunnels, polyurethane-based chemical grouting materials were successfully used to address frequent water inflow issues at tunnel crowns, ensuring that construction progress remained unaffected.

4.3 Improved Blasting and Excavation Methods

To achieve more precise blasting results and minimize environmental impact, the application of digital simulation and intelligent blasting technologies has become increasingly important. By constructing three-dimensional geological models and using numerical simulation software to predict the propagation paths of stress waves and the extent of damage from blasts, drilling layouts and explosive charges can be optimized for the best blasting effect. With the aid of computer-aided design (CAD) software, construction teams can simulate blasting plans, significantly reducing the impact on surrounding rock mass while improving safety.

Improving excavation techniques is another effective way to enhance construction safety. Step-by-step excavation and pre-splitting blasting techniques are typical examples. Step-by-step excavation involves progressively excavating portions of the tunnel, with initial support completed before expanding to the remaining sections, thus reducing the risks associated with large-scale excavation. Pre-splitting blasting involves creating artificial cracks by detonating a ring of boreholes before the main blasting area, reducing the impact of the primary blast on the surrounding rock. For a large diversion tunnel project at a hydroelectric station, implementing these excavation methods greatly reduced rock collapses during construction, ensuring smooth project progress.

4.4 Innovative Solutions to Enhance Support and Lining Quality

The application of new materials has revolutionized tunnel support and lining structures. Fiber-reinforced concrete, with its outstanding mechanical properties and crack resistance, has been widely used in tunnel lining construction. This material significantly enhances the durability and safety of tunnel structures, extending their service life. High-toughness steel, with its excellent ductility and fatigue resistance, strengthens the overall stability of support structures. Another important innovation is the intelligent management system. By integrating the Internet of Things (IoT) with big data analytics, it has become possible to create an intelligent management system for real-time monitoring of support structures. By analyzing data collected from sensors, the system can promptly identify potential safety hazards and send out alerts, guiding field personnel to take appropriate protective measures. Some tunnel projects have adopted IoT-based intelligent monitoring platforms to provide 24/7 monitoring of support structure health, greatly enhancing the scientific and effective management of construction safety.

5 Conclusion

This paper provides an in-depth analysis of the key issues surrounding tunnel construction safety under complex geological conditions, including rock mass stability, groundwater control, blasting and excavation techniques, and support and lining solutions. It presents a range of innovative safety measures that enhance both the safety and efficiency of tunnel projects while offering valuable theoretical foundations and practical guidance for the development of related engineering technologies.

As geological conditions and technological challenges continue to evolve, future research should place a greater emphasis on interdisciplinary collaboration, integrating knowledge from fields such as geology, materials science, and information technology to explore smarter and more environmentally friendly construction methods. Additionally, with the growing impact of global climate change on the geological environment, studying ways to ensure tunnel construction safety under extreme climate conditions has become increasingly crucial. Through continuous technological innovation and management optimization, we can better address the challenges posed by complex geological environments and drive tunnel engineering technology toward a more sustainable future.

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