

# A Review of the Development of Tunnels and Support Systems

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**Abstract:** Against the backdrop of continuous advancements in infrastructure construction, tunnel engineering, as a critical component of transportation, water conservancy, and other fields, is becoming increasingly prominent in importance. Tunnel construction faces numerous challenges, such as complex geological conditions and high-stress environments. The support system, as the core element ensuring tunnel stability and safety, has seen a crucial evolution in its development and technological innovations. From the early simple support structures to today's diversified composite support systems, significant progress has been made in materials, structural forms, and construction techniques. The development and application of new materials have enhanced the strength and durability of support structures; advanced structural design concepts enable support systems to better adapt to complex geological conditions; and the continuous optimization of construction techniques has improved efficiency and quality. This paper aims to provide a comprehensive review of the development of tunnels and support systems, outlining their evolutionary trajectory, analyzing key technological innovations, and discussing current challenges and future trends. It seeks to offer valuable insights for the construction and advancement of tunnel engineering.

**Keywords:** Tunnel, Support, Review.

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## 1. Introduction

Currently, tunnel construction is flourishing globally, and China has become a tunnel powerhouse with its massive construction scale and advanced technology. As of the end of 2022, the total length of tunnels in China has reached 48762 kilometers and continues to grow. There are various types of tunnels, covering areas such as highways, railways, subways, and water conservancy, to meet different transportation and infrastructure needs<sup>[1]</sup>.

The support system, as a key component of tunnel construction, has achieved significant development results. In terms of materials, high-performance concrete, new types of steel, and other materials are widely used to enhance the strength and durability of supporting structures. In terms of structural form, it has evolved from traditional single support to composite support, such as anchor rod and shotcrete combined support, steel arch and steel mesh composite support, etc., which can better adapt to complex geological conditions.

The continuous innovation of construction technology and the application of advanced equipment such as shield tunneling machines and tunneling machines have improved the automation and intelligence level of construction. At the same time, information technology such as BIM and GIS has been promoted in tunnel construction, achieving precise management and efficient collaboration of construction. However, tunnel construction still faces challenges such as complex geology and safety risks, and the support system needs to be continuously optimized and upgraded to ensure the long-term stability and safety of tunnel engineering<sup>[2]</sup>.

## 2. Types and Characteristics of Tunnels

### (1) Railway Tunnels

Railway tunnels are critical structures enabling rail lines to traverse natural barriers such as mountains and rivers. By shortening route distances and reducing gradient constraints, they significantly enhance operational speed and safety while adapting to complex terrain and lowering long-term costs. Their design must accommodate railway load requirements, incorporate auxiliary systems such as ventilation, lighting, and drainage, and employ construction methods—including drill-and-blast, tunnel boring machine (TBM), or shield tunneling—tailored to geological conditions to ensure structural stability and ride comfort.

### (2) Highway Tunnels

Highway tunnels serve as essential infrastructure for optimizing road alignment and improving traffic safety. They reduce travel distances, mitigate accident risks, and facilitate passage through challenging terrains such as mountainous or river-crossing areas. Design considerations include vehicular traffic demands and geological constraints, with support measures such as rock bolts and shotcrete applied during construction. Techniques like drill-and-blast, the New Austrian Tunneling Method (NATM), or shield tunneling are employed to ensure structural integrity and driving comfort. Additionally, ventilation, lighting, and fire protection systems are optimized for operational safety.

### (3) Subway Tunnels

Subway tunnels form the backbone of urban rail transit systems, alleviating surface traffic congestion and enabling high-capacity, rapid transit to enhance urban mobility. Their design must meet operational requirements for train movement and passenger comfort, integrating critical systems such as ventilation, lighting, and disaster prevention. Construction methods—including shallow cover tunneling and shield tunneling—are selected based on urban geological conditions to minimize ground settlement and ensure structural safety and operational efficiency.

#### (4)Hydraulic Tunnels

Hydraulic tunnels are vital components of water conservancy projects, facilitating functions such as water diversion, drainage, and conveyance to optimize resource allocation and improve flood control, irrigation, and power generation. Their design must withstand hydraulic pressure and flow-induced erosion, emphasizing alignment optimization and lining structures to ensure smooth water passage and impermeability. Construction techniques—such as drill-and-blast, shield tunneling, or pipe jacking—are implemented with tailored support and waterproofing measures to guarantee long-term structural stability and operational safety under varying geological conditions.

### 3. Tunnel Support Systems: The Critical Safeguard in Tunnel Engineering

As the fundamental safety measure in tunnel construction, tunnel support systems play an indispensable role throughout all critical phases of both construction and operation.

During the construction phase, tunnel excavation disrupts the original stress equilibrium of the surrounding rock, leading to stress redistribution. Localized stress concentrations may result in hazardous conditions such as collapses and roof falls. At this stage, support structures—including rock bolts, shotcrete, and steel arches—act as robust defensive barriers, actively applying restraining forces to control rock deformation and prevent excessive convergence into the tunnel. This ensures a relatively safe working environment for personnel and equipment. For instance, in weak rock zones, delayed or inadequate support could trigger large-scale deformation and tunnel collapse within a short timeframe, causing project delays, casualties, and significant economic losses. Properly designed support systems substantially mitigate such risks, ensuring smooth construction progress<sup>[3]</sup>.

Under complex geological conditions—such as fault fracture zones or weak surrounding rock—where stability is compromised and groundwater activity is frequent, support systems become even more critical. They not only block groundwater infiltration (preventing rock softening and strength reduction) but also enhance the overall load-bearing capacity through interaction with the surrounding rock. For example, when traversing fault zones, high-strength support materials and optimized configurations can integrate fractured rock masses into a cohesive structure, distributing loads evenly and preventing localized instability from triggering catastrophic failures. For different tunnel types, support design and construction must adapt to distinct functional and geological requirements<sup>[4]</sup>:

- (1) Railway tunnels demand ultra-high strength and stability to withstand dynamic train loads.
- (2) Highway tunnels prioritize driving safety and comfort, requiring integrated ventilation and lighting considerations.
- (3) Subway tunnels, often constructed in urban subterranean spaces, necessitate precision-engineered supports for confined construction conditions.
- (4) Hydraulic tunnels require exceptional waterproofing to resist high water pressures.

Accordingly, support systems employ tailored construction methods and scientifically optimized parameters to form a

synergistic load-bearing system with the surrounding rock. For example, in subway shield tunneling, precise control of thrust pressure and segment assembly ensures structural integrity and watertightness, preventing leaks and ground settlement<sup>[5]</sup>.

Through these comprehensive measures, tunnel support systems guarantee structural safety during construction and operation, extend service life, minimize operational risks, and deliver reliable infrastructure for transportation and water management.

### 4. Application and Key Core Technologies of Tunnel Support Systems

#### 1. Forepoling

Forepoling involves installing high-strength, corrosion-resistant rock bolts ahead of the tunnel face and grouting them to create a pre-support system, with precise design of bolt diameter/angle ensuring reliable bonding with surrounding rock. The technique requires adequate longitudinal overlap and connection to steel arches for integrated load-bearing capacity, while real-time stress monitoring allows dynamic parameter adjustments to control deformation and ensure excavation safety in unstable ground conditions.

#### 2. Pipe Roofing

Pipe roofing utilizes large-diameter steel pipes installed in an optimized pattern ahead of the face to form a protective canopy, particularly effective in weak strata or urban tunneling. The system's performance depends on precise pipe alignment/verticality control, grout reinforcement of surrounding rock, and robust longitudinal connections to create a combined pipe-rock load-bearing structure that prevents collapses during excavation beneath sensitive areas.

#### 3. Pipe Curtain

This shallow tunneling solution creates a continuous enclosure through tightly spaced, grout-filled steel pipes installed using directional drilling for minimal environmental impact. The system's effectiveness relies on precise pipe alignment, transverse connections for structural rigidity, and real-time monitoring to adjust support parameters as needed when working in soft ground or urban environments with strict deformation controls.

#### 4. Advance Grouting

By injecting specially formulated grouts (rapid-setting, micro-expansive) into rock fractures ahead of excavation, this technique improves ground self-support capacity through controlled consolidation. Success requires dynamic adjustment of grout mixes based on permeability, careful pressure/flow monitoring to ensure proper penetration without over-disturbance, and post-grouting verification with potential secondary treatments to achieve design reinforcement objectives.

#### 5. Horizontal Jet Grouting

This method forms interlocking, soil-cement columns through high-pressure rotational injection of cementitious slurry, creating an improved ground arch around the excavation. Implementation demands specialized high-RPM equipment, real-time quality control of column geometry/overlap, and careful utility avoidance, with particular effectiveness in water-bearing strata where it

provides both structural support and groundwater control.

## 6. Ground Freezing

The temporary artificial ground freezing technique establishes a load-bearing frozen arch by circulating chilled brine through strategically placed pipes, with critical attention to uniform temperature distribution and frost heave management. Particularly valuable for water-rich strata and urban projects, it requires comprehensive thermal/deformation monitoring throughout both freezing and controlled thawing phases, typically combined with permanent support systems for long-term stability.

## 5. Conclusion

As the fundamental safeguard for underground construction safety, tunnel support technologies and their key techniques are fundamentally centered on surrounding rock stability management. Forepoling (advance rock bolting) establishes early load-bearing capacity through pre-support mechanisms, where the bonding interaction between bolts and rock mass is critical - requiring precise material selection, installation angle control, and longitudinal overlap design to ensure continuous support integrity.

The pipe roofing and pipe curtain techniques employ large-diameter or densely-arranged steel pipes to form protective structures. Pipe roofing excels in weak ground conditions, while pipe curtain specializes in shallow tunnel enclosure support. Both systems depend on grout reinforcement to achieve synergistic rock-pipe load transfer, with construction precision and reliable longitudinal connections being decisive factors for performance.

Ground improvement techniques include advance grouting and horizontal jet grouting. The former consolidates fractured rock through controlled grout penetration, demanding dynamic adjustment of mix proportions, injection pressure and range according to rock permeability. The latter creates continuous soil-cement columns via high-pressure spraying, where equipment parameters and process compatibility determine column quality. Both methods require post-construction verification and potential remedial treatments (re-grouting or additional spraying) to optimize performance.

Ground freezing serves as a specialized solution, forming temporary frozen earth curtains through brine circulation. The technology's efficacy lies in precise freeze pipe configuration and temperature control, requiring careful balance between frost heave effects and structural requirements. Equally critical is the controlled thawing process design to prevent collapse risks during system decommissioning.

Practical implementation requires integrated application based on geological conditions and project demands. Weak strata typically combine pipe roofing with advance grouting, while shallow tunnels emphasize pipe curtain tightness and transverse connectivity. Real-time performance monitoring - tracking bolt stresses, pipe deformation, grouting pressures, etc. - enables dynamic parameter optimization, forming the core of modern support system management.

Future advancements will focus on lightweight materials, high-efficiency processes, and intelligent monitoring systems, driving the evolution toward smarter, more reliable support solutions for underground construction challenges. Emerging smart materials and AI-powered monitoring platforms are expected to revolutionize traditional practices, enabling predictive maintenance and adaptive support systems.

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