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Technology for Enhancing the Disaster Resistance of Highway Tunnels under Extreme Weather Conditions

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Abstract: Tunnels, as critical control projects in highway transportation, play a direct role in the stability of regional transportation networks and the safety of people's lives and property. This paper systematically analyzes the disaster mechanisms of extreme weather on highway tunnels, constructs a scientific risk assessment system, and proposes a technology system for enhancing disaster resistance from the perspective of the full lifecycle of design, operation, and emergency response. This system covers site selection optimization, structural reinforcement, monitoring and early warning, maintenance and reinforcement, and emergency recovery, providing theoretical support and technical references for the planning, design, construction, and operation management of highway tunnels in regions prone to extreme weather.

Keywords: Extreme weather; Highway tunnels; Disaster resistance; Risk assessment; Structural reinforcement; Monitoring and early warning; Emergency response

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1. Introduction

Highway tunnels hold a significant position in modern transportation networks, especially in complex terrain areas such as mountains and hills, where they are indispensable. They offer distinct advantages such as shortening transportation distances, improving driving conditions, and protecting the ecological environment. However, as semi-enclosed underground structures, tunnels are significantly affected by both direct and indirect effects of meteorological conditions [1]. In recent years, global warming has led to an increasing frequency, intensity, and scope of extreme weather events, such as heavy rainfall triggering mountain torrents and mudslides at tunnel entrances as well as water accumulation inside tunnels, heavy snowfall causing snow accumulation at tunnel entrances and the freezing and blockage of drainage systems inside tunnels, low-temperature freeze-thaw cycles causing structural damage, and strong winds and sandstorms affecting operations at tunnel entrances, posing severe challenges to the safe operation of highway tunnels.

2. Disaster mechanisms and risk assessment of extreme weather on highway tunnels

2.1. Analysis of disaster mechanisms of different extreme weather events

2.1.1. Mechanism of rainstorm disasters

Continuous heavy rainfall from rainstorms can lead to instability and collapse of the slopes at tunnel entrances, and even trigger mountain torrents and mudslides. When water accumulation increases sharply and drainage is inadequate, water can easily accumulate inside tunnels, affecting traffic safety. Rainwater can seep into the structure through cracks in the lining, construction joints, and other areas, causing steel reinforcement corrosion and reducing the structural load-bearing capacity.

2.1.2. Mechanism of heavy snow disasters

Snow accumulation at tunnel entrances, if not cleared promptly, can easily block the entrances and disrupt traffic. Meltwater can seep into the lining and the foundation at tunnel entrances, freezing at low temperatures and causing frost heave cracking of the lining and frost heave deformation of the foundation. Heavy snowfall can lead to a sudden drop in visibility and icy road surfaces, increasing driving risks. Prolonged heavy snowfall can also result in snow and ice accumulation on ancillary facilities such as ventilation, lighting, and power supply and distribution systems, affecting their normal operation and even causing damage.

2.1.3. Mechanism of low-temperature freeze-thaw disasters

After porous materials such as lining concrete and masonry structures at tunnel entrances absorb moisture, they experience volume expansion due to freezing at low temperatures, generating frost heave stress. When the temperature rises and thaws, moisture migration forms pores and cracks. After multiple freeze-thaw cycles, the concrete surface exhibits sanding and spalling, internal cracks expand and lead to cracking, and strength and durability decline. Simultaneously, it can also cause the drainage system to freeze and clog, reducing the sealing performance of waterproof materials such as rubber waterstops and exacerbating lining leakage.

2.1.4. Mechanism of strong wind and sandstorm disasters

Strong winds create negative pressure zones or vortices at tunnel entrances, leading to ventilation disorders inside the tunnel. They carry sand and gravel that strike structures and ancillary facilities at the entrance, causing surface wear and structural damage. During sandstorms, sand and dust accumulate and block drainage channels and vents, while fine sand infiltrates the tunnel interior, adhering to equipment surfaces, affecting operational efficiency and service life, and in severe cases, causing a sudden drop in visibility inside the tunnel, leading to traffic congestion and accidents.

2.2. Identification of weak links in disaster resistance of highway tunnels

Based on the mechanisms of extreme weather disasters and the characteristics of tunnel structures and operations, five weak links in disaster resistance have been identified: First, weaknesses in site selection and route layout, such as tunnel entrances located in disaster-prone areas, routes with small angles to prevailing wind directions, and entrances at the bottom of valleys or on windward slopes. Second, weaknesses in entrance protection systems, such as inadequate slope protection measures, imperfect interception and diversion systems for mountain floods and debris flows, and unreasonable design of structures for snow, ice, and wind-sand prevention [2]. Thirdly, the main structure is vulnerable to disasters, with issues such as design flaws in lining anti-seepage, insufficient concrete strength and thickness, inadequate freeze-thaw resistance, and unreasonable surrounding rock support parameters. Fourthly, drainage and ancillary facilities are weak, including inadequate drainage system design, lack of disaster protection in the power supply and distribution system, insufficient redundancy in ventilation and lighting design, and low reliability of fire emergency systems. Fifthly, operational management and emergency response are inadequate, with problems such as an imperfect extreme weather monitoring system, an unsound disaster warning mechanism, substandard operational maintenance, and poorly targeted emergency plans.

2.3. Risk assessment system for tunnel disasters under extreme weather conditions

2.3.1. Risk level classification

Based on relevant standards and considering the impact of disasters, the risk levels are classified into four categories: Level I (low risk), characterized by low hazard of disaster-causing factors, low vulnerability of the disaster-bearing body, strong disaster resistance, extremely low probability of disaster occurrence, and minimal losses; Level II (medium risk), with relatively low hazard of disaster-causing factors, relatively low vulnerability of the disaster-bearing body, relatively strong disaster resistance, low probability of disaster occurrence, and relatively small losses; Level III (high risk), involving relatively high hazard of disaster-causing factors, relatively high vulnerability of the disaster-bearing body, relatively weak disaster resistance, relatively high probability of disaster occurrence, and relatively large losses; Level IV (extremely high risk), marked by high hazard of disaster-causing factors, high vulnerability of the disaster-bearing body, weak disaster resistance, high probability of disaster occurrence, severe losses, and potential tunnel paralysis and casualties [3].

2.3.2. Construction of risk assessment model

The assessment model is constructed using the comprehensive index method. After standardizing the indicators, the comprehensive risk index is calculated by combining them with their respective weights to determine the risk level. The formula for calculating the comprehensive risk index is as follows:

$$R = \sum_{i=1}^{n} W_i \times S_i$$

Where, R represents the comprehensive risk index; W_i is the weight of the i-th indicator; S_i is the standardized value of the i-th indicator; and n is the total number of indicators. The indicators are standardized using the extreme value method to convert them into values within the range of 0–1. Positive standardization is applied to hazard-causing factors and vulnerability indicators of disaster-bearing bodies, while negative standardization is used for disaster resilience indicators. Tunnels with high and extremely high risks require targeted disaster resilience enhancement measures, while those with medium and low risks should adopt conventional disaster resilience measures and undergo regular monitoring and assessment [4].

3. Key technologies for disaster resilience design of highway tunnels under extreme weather conditions

3.1. Tunnel site selection and route optimization technology based on extreme weather conditions

3.1.1. Site avoidance technology under extreme weather zoning

Conduct a comprehensive survey and zoning study of regional extreme weather conditions, combining historical meteorological data, topography, and the distribution of geological disasters. Utilize GIS spatial analysis technology to delineate high-, medium-, and low-risk areas. High-risk areas include landslide and debris flow-prone regions with frequent heavy rainfall, as well as high-altitude mountainous areas with concentrated snowstorms. Site selection should adhere to the principle of “avoiding the heavy and choosing the light”, prioritizing low-risk areas. When it is necessary to traverse medium- and high-risk areas, the length within high-risk areas should be minimized, and the core disaster regions should be avoided [5]. Additionally, conduct specialized meteorological surveys to collect extreme weather observation data from the past 30 years, analyze occurrence patterns and evolutionary trends, and provide precise data support.

3.1.2. Optimized design of route alignment and tunnel entrance location

Multiple route alignment options should be compared and evaluated. In areas prone to frequent strong winds, the axis should be arranged as perpendicular as possible or at a large angle to the prevailing wind direction to reduce the impact of strong winds on the tunnel entrance. In regions with a high risk of heavy rainfall, avoid valleys with large catchment areas to mitigate the threat of mountain torrents and debris flows. The tunnel entrance should be located in areas with stable terrain and gentle slopes, avoiding steep slopes. In areas with a high risk of heavy rainfall, the slope gradient should be controlled within a range of 1:1.5 to 1:2.0, and retaining and protective measures should be implemented. The tunnel entrance should be positioned away from areas where mountain torrents and debris flow and accumulate. In regions with a high risk of heavy snowfall, choose locations at higher elevations with good drainage, adjusting the orientation to face away from the wind and towards the sun.

3.2. Disaster-resistant protection technologies for tunnel entrances

3.2.1. Anti-slip and anti-erosion reinforcement technologies for tunnel entrance slopes/front slopes

A combined “active protection + passive protection” approach should be adopted to address slope disasters triggered by heavy rainfall. Active protection measures include anchor bolt (cable) reinforcement, shotcrete and rock bolt support, and lattice beam reinforcement, which enhance the soil’s shear strength and the overall stability of the slope. Passive protection measures include retaining walls, anti-slide piles, and rockfall barriers, which prevent slope sliding and the collapse of rocks. Additionally, geosynthetic materials can be laid or mortar-rubble masonry can be used for slope surface protection to enhance erosion resistance.

3.2.2. Design of mountain torrent/debris flow interception and diversion systems

A well-designed interception and diversion system ensures that mountain torrents and debris flow safely bypass the tunnel entrance. The interception system comprises intercepting ditches, debris dams, and diversion dikes, which are respectively used to intercept runoff from slopes, block large debris in debris flows, and guide mountain torrents and debris flows away from the tunnel entrance. The diversion system includes flood discharge ditches and flood discharge tunnels; the flood discharge ditches are designed based on extreme rainstorm flow rates, while the flood discharge tunnels are used to directly divert debris flows from high-risk areas. The system employs high-strength, corrosion-resistant materials such as reinforced concrete and mortar-rubble masonry, with regular cleaning and maintenance to prevent blockages.

3.2.3. Design of tunnel entrance structures for snow, ice, and wind-blown sand prevention

Snow prevention is achieved through the use of snow fences and snow accumulation platforms. The snow fences are installed on the upstream side of the tunnel entrance, with a height of 3–5 meters and a spacing of 5–10 meters. The snow accumulation platforms are designed based on the maximum snow accumulation and are equipped with drainage slopes. Ice prevention employs electric heating or hot water melting systems, complemented by the application of thermal insulation materials and the wrapping of pipeline insulation layers [6]. Wind-blown sand prevention utilizes windbreak walls and windproof nets; the windbreak walls are 4–6 meters high and cover 30–50 meters on both sides of the tunnel entrance, while the windproof nets have a pore size of 0.5–2 millimeters to filter sand and dust.

3.3. Disaster-resistant reinforcement design techniques for the main tunnel structure

3.3.1. Reinforced design for leakage resistance of the lining structure

A composite waterproofing system consisting of “waterproof concrete + waterproof layer + water stop” is adopted. The material selected is waterproof concrete with an impermeability grade not lower than P8, mixed with expansion agents and water-reducing agents, while the waterproof layer is made of high-quality waterproof membranes. In terms of structural design, the lining thickness is optimized (not less than 30 cm), the waterproof layer is fully laid with an overlap width of not less than 10 cm, and buried and back-adhered water stops are installed at construction joints and deformation joints. During construction, quality control is strengthened, water pressure tests are conducted after completion, and any leakage areas are promptly addressed [7].

3.3.2. Frost resistance design

The material selected is concrete with a frost resistance grade not lower than F200, mixed with air-entraining agents, and using high-quality aggregates and HRB400 grade or higher steel bars. In terms of structural design, the mix ratio is optimized to control the water-binder ratio below 0.45, the lining thickness at the tunnel entrance is increased, and a protective coating is applied. Protective measures include insulating the tunnel entrance lining, optimizing the ventilation system to maintain internal temperatures, and regularly inspecting and repairing lining cracks.

3.3.3. Design for wind load and temperature stress resistance

In wind resistance design, wind loads under maximum wind speeds are calculated, the wind stability of tunnel entrance structures is verified, lining reinforcement is optimized, and ventilation shafts and fans are reasonably arranged [8]. For temperature stress design, temperature expansion joints are set at intervals of 20–30 m, low-heat cement is selected to optimize the mix ratio, and during construction, layered pouring and water curing are employed to control the temperature difference between the interior and exterior.

3.3.4. Design enhancement under the coupled effects of seismic activity and extreme weather conditions

Conduct risk assessments for earthquakes and extreme weather to determine design loads under coupled effects, and employ numerical simulations to analyze structural stress and deformation patterns. Adopt performance-based seismic design, select concrete with good ductility, increase reinforcement ratios, and establish plastic hinge zones; optimize surrounding rock support parameters, and strengthen protection at vulnerable locations such as tunnel entrances and shallow-buried sections; enhance the overall structural integrity and tightness to prevent exacerbated damage from overlapping disasters [9].

3.4. Disaster-resistant design techniques for tunnel drainage systems

Adhere to the principle of “combining prevention, drainage, interception, and blocking” to establish a three-dimensional drainage system consisting of “horizontal + longitudinal + vertical” components. Horizontal drainage includes pavement gutters and central divider drainage channels; longitudinal drainage includes side wall drainage blind pipes and longitudinal drainage pipes; vertical drainage includes drainage shafts and weep holes. The system is verified based on a once-in-a-century storm intensity, utilizing high-quality materials such as HDPE pipes and reinforced concrete pipes. Drainage pump stations are configured with one active and one standby pump or multiple active and one standby pump. In cold regions, pipe insulation and pump station heating measures are implemented, with debris cleared promptly during snowmelt seasons.

3.5. Disaster-resistant design techniques for ancillary facilities

3.5.1. Redundancy design of ventilation and lighting systems for extreme weather resistance

The ventilation system is equipped with a standby ventilator, which is of a corrosion-resistant, ice-and-snow-resistant, and sandstorm-resistant model. The pipelines are insulated and protected, and the ventilation openings are equipped with wind-sand and ice-snow prevention devices. The lighting system employs a dual system of "main lighting + emergency lighting", with LED fixtures selected for the main lighting. The emergency lighting operates on an independent power supply, and the fixtures have a protection rating of no less than IP65. Enhanced lighting is installed at the tunnel entrance section.

3.5.2. Rainstorm, ice-snow, and lightning protection technologies for the power supply and distribution system

Rainstorm prevention measures include positioning equipment in high-elevation areas with good drainage, ensuring the enclosure protection rating is no less than IP54, and implementing cable trench drainage and joint waterproofing. Ice-snow prevention measures involve equipment insulation and heating, the selection of cold-resistant cables, and regular clearing of snow and ice. For lightning protection, a comprehensive lightning protection and grounding system is constructed, incorporating lightning rods and arresters, with a grounding resistance of less than 4 Ω. Dual power supplies and backup generators are employed, along with enhanced equipment monitoring.

3.5.3. Design enhancements for disaster resilience in fire protection and emergency systems

The fire protection system utilizes an "automatic + manual" fire extinguishing system, with dual water sources and backup fire pumps, and pipeline insulation and protection. The emergency system improves emergency access design, establishes independent emergency communication and broadcasting systems, and maintains adequate emergency supplies based on disaster types. The fire protection and emergency systems are linked with the monitoring and early warning system to enhance emergency response efficiency.

4. Disaster resilience enhancement technologies for highway tunnels during operation under extreme weather conditions

4.1. Extreme weather monitoring and early warning technology

Establish a system of "real-time monitoring + data analysis + precise early warning" to enhance disaster prediction and response capabilities. The monitoring system covers four major parameters: meteorology, structure, environment, and transportation. It employs anti-interference high-precision equipment and combines wireless and wired data transmission methods to establish a unified data platform [10]. Based on monitoring and historical data, machine learning algorithms are used to construct early warning models. Considering regional characteristics, multiple methods are employed to determine early warning thresholds, dividing early warning levels from Level IV (blue) to Level I (red), corresponding to low to extremely high risks. A multi-channel early warning dissemination mechanism is established to ensure timely information delivery to operational management personnel, drivers and passengers, and relevant departments.

4.2. Disaster resistance maintenance and reinforcement technology during operation period

Establish a regular maintenance mechanism, develop detailed maintenance plans, specify content, frequency, responsible entities, and quality standards, and increase maintenance frequency for high-risk tunnels. Maintenance tasks include inspecting and repairing entrance protection facilities, clearing and dredging drainage systems, inspecting and repairing main structures, and inspecting and maintaining ancillary facilities, with maintenance records established accordingly. For defects and weak points identified during operation, specialized reinforcement techniques such as lining crack sealing and grouting, leakage plugging, slope anchor bolt supplementation, and equipment upgrades and replacements are employed. Regularly evaluate maintenance effectiveness based on indicators such as structural condition, equipment operation, and disaster resistance capacity, and promptly adjust and optimize measures.

4.3. Tunnel traffic control and diversion technologies under extreme weather conditions

Establish a mechanism of "early warning–response–control–recovery" and formulate measures based on warning levels: maintain normal operations and issue reminders at Level IV; restrict traffic flow at Level III, limit the passage of large trucks and dangerous goods vehicles, and enhance patrols and environmental improvements; implement traffic control at Level II, close certain lanes or impose speed limits, guide detours, and clear hazards at tunnel entrances; immediately close the tunnel at Level I, set up warning signs, and have emergency teams on standby. Utilize intelligent diversion technologies by leveraging monitoring systems and intelligent platforms to manage traffic flow, install guidance signs, and disseminate information through navigation apps to guide vehicles inside the tunnel to park or evacuate in an orderly manner, and establish emergency refuge areas.

5. Emergency response and post-disaster recovery technologies for highway tunnels under extreme weather conditions

5.1. Emergency response technology system

Adhere to the principles of "prevention-oriented, rapid response, scientific disposal, and people-first" to establish an emergency response system covering organization, plans, teams, and materials. Establish a hierarchical and collaborative emergency organization system, clarify the responsibilities of each department, and strengthen coordination and joint drills; develop three-tier emergency plans (overall, specialized, and on-site response), and regularly revise and improve them; form professional emergency rescue teams equipped with specialized equipment and protective gear, and enhance training and drills; establish emergency material reserve warehouses, reasonably allocate rescue equipment, protective gear, medicines, etc., and establish management systems and allocation mechanisms.

5.2. Rapid post-disaster assessment and repair techniques

After a disaster, it is essential to promptly conduct assessments of disaster losses, structural safety, and environmental impacts. A combination of on-site inspections and numerical simulations should be employed to evaluate structural safety, categorizing damage into four levels: slight, moderate, severe, and catastrophic. Slight damage can be repaired using methods such as surface sealing and localized grouting; moderate damage can be reinforced through pressure grouting and the application of carbon fiber sheets; severe damage necessitates measures like demolition and reconstruction, as well as landslide control; and catastrophic damage requires consideration of reconstruction or route adjustments. Repairs should adhere to the principles of "safety first, restoring functionality before improvement, and scientific repair", with enhanced quality and safety management.

5.3. Post-disaster operational recovery and optimization adjustments

Following tunnel repairs, comprehensive acceptance inspections and trial runs should be conducted, accompanied by strengthened monitoring and a gradual resumption of traffic. Public awareness campaigns should be launched for drivers and passengers. Based on post-disaster assessments and emergency response experiences, monitoring and early warning systems, disaster resilience maintenance plans, traffic control strategies, and emergency response plans should be optimized to continuously enhance the tunnel's disaster resilience and operational safety.

6. Conclusion

Enhancing the disaster resilience of highway tunnels under extreme meteorological conditions is a multi-stage, systematic endeavor. This paper draws the following conclusions:

(1) Extreme weather poses a direct threat to tunnel safety and triggers secondary disasters, with clear weak points identified for disaster resilience, providing targeted bases for risk assessment and technological improvement;

(2) The proposed key technological system for disaster-resilient design, from site selection optimization to the provision of ancillary facilities, enhances the inherent disaster resilience of tunnels;

(3) Establish a technological system for enhancing disaster resilience during the operational period, enabling dynamic monitoring and effective response to extreme meteorological disasters;

(4) Construct a technological system for emergency response and post-disaster recovery, ensuring rapid response and operational restoration, and continuously improving disaster resilience capabilities.

Disclosure statement

The authors declare no conflict of interest.

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