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Contents

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ARTICLE

Application of Energy Saving and Consumption Reduction Technology in Power Transmission and Distribution Lines

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ABSTRACT

The power system is developing towards high voltage and large capacity. As a physical node of the energy transmission network, the metal tool is subject to complex electrical and mechanical loads. The resistance loss and additional hysteresis loss of its body have become the key bottlenecks affecting the transmission efficiency of the power grid. The eddy current thermal effect generated by traditional galvanized steel tools in alternating electromagnetic field environment leads to significant energy consumption accumulation, and the unstable contact resistance at the contiguous part aggravates the risk of non-uniform temperature rise of the conductor. The engineering application of new aluminum alloys and carbon fiber composites breaks the inherent electromagnetic characteristics of metal materials, and combines the research and development of surface treatment and structural lightweight technology to build an energy-saving technology matrix from material conductivity optimization to structural form redesign. This research system aims to solve the inherent bottleneck of energy consumption in the metal link in the transmission and distribution lines, and provides scientific basis for improving the economic indicators of electricity transmission and system reliability.

1. Introduction

The power transmission and distribution network carries the core functions of power transmission, and its line energy loss directly affects the economics and environmental benefits of power supply. Electrical metal tools play an irreplaceable role in ensuring the mechanical strength and electrical connectivity of the line. The ineffective energy consumption caused by resistance effect and electromagnetic induction during operation of conventional metal tools has not been fully paid attention to for a long time. The application of aluminum alloys and composite materials has significantly improved the conductivity of the metal tool, and combined with the eddy current suppression structural design, the electromagnetic conversion loss can be reduced from the source. Improved

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coating process effectively suppresses the increase in contact resistance caused by metal surface oxidation. Integrated design reduces material usage while ensuring mechanical strength, forming a multi-dimensional energy-saving effect. Together, these technologies constitute a technical system for energy consumption control of power tools [1].

2.Overview of electric appliances

(I) Definition and classification of power equipment

Electric power metal tools specifically refer to basic components used to connect, fix and protect various components in overhead transmission and distribution lines. This type of metal accessories constitutes the physical framework for the installation and operation of the power grid. Its classification system is based on functional realization. The connecting tool undertakes the series connection task between the drape clamps or tension clamps. The connecting tool specializes in handling repair operations and daily connection needs after wire damage (see Figure 1). Protective tools focus on the safe operation protection field of key equipment such as insulators to avoid corona discharge and mechanical damage affecting system stability. The wire pulling tool exerts structural anchoring function at the base of the tower to maintain the overall structural stress balance. Each type adopts differentiated material formulas and structural forms based on specific physical characteristics and functional goals. For example, the model size in the tension string group is related to the vibration characteristics of the conductor, and the inclination parameters of the overhang line affect the safety margin of the air bias. These standardized technical specifications jointly build the basic structure of electric power tools.

(II) The role of power tools in power transmission and distribution lines

Electric power tools essentially play the role of adhesive in the grid structure, connecting the dispersed wires and insulators into a continuous transmission corridor. The tension-resistant wire clip accurately controls the conductor tension distribution against the uncertain effects of wind loads, and the overhang combination maintains the conductor trajectory in the vertical direction to reduce the probability of dancing accidents (see Table 1). The conductor connection tube maintains the transmission cross-sectional area unchanged when repairing the broken strand defect, thereby ensuring stable electrical performance. The anti-vibration hammer targets the metal fatigue hazards formed by breeze oscillation and extends the service cycle of the conductor. The mechanical connection system composed of this type of metal components ensures the structural integrity of the line when it encounters extreme weather. The physical characteristics of its conductive contact surface directly determine the line loss level. The accumulation of oxide layer on the metal surface may lead to an abnormal increase in contact resistance. The edge electric field control capability of the metal design is related to the electric field distribution of the insulator string surface, and is related to the total corona loss and the radio interference level. These multi-dimensional functions are nested together to ensure the long-term and reliable operation of power transmission and distribution systems.

3.Energy-saving and consumption-reducing technology of electric tools

(I) New material application technology

The current innovation in power metal materials focuses on the coordinated optimization of conductive mechanism and mechanical properties, and aluminium alloy materials have become the mainstream trend to replace traditional cast iron. Due to the characteristics of the relative permeability approaching 1, the aluminum alloy member significantly reduces the hysteresis loss in the alternating magnetic field, and its body resistivity decreases, so that the intrinsic impedance of the current transmission path can be compressed. The application of carbon fiber reinforced composite materials in the field of overhanging wire clips shows unique advantages. This non-metallic material completely avoids the conditions for forming closed magnetic circuits and fundamentally eliminates the inherent eddy current thermal effects of ferromagnetic materials. The polymer composite conductive material acts as a transition layer at the metal joint node. Its specific carrier concentration distribution mode can effectively harmonize the potential step phenomenon between different metals and reduce the carrier scattering probability of the connection interface. This type of material solution verifies the temperature rise suppression capability in the ±800kV ultra-high voltage project, and the overall linear loss rate of the transmission corridor shows structural improvement. The practice of metal-based ceramic composites in heavily corroded areas shows that the oxide film generated in-situ on the surface simultaneously solves the dual issues of chemical corrosion protection and contact resistance stability.

(II) New material application technology

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(III) Surface treatment technology

Microarc oxidation technology forms a micro-scale ceramic protective layer in the application of tension-resistant wire clip surfaces. This α-Al_2O_3 crystal structure controls the surface contact resistance drift rate to three thousandths per month while maintaining the substrate conductivity. Cold spray pure copper coating treatment carried out molecular-level recombination of the current-carrying surface of the equipment line clamp. SEM observations showed that the optimal growth of the copper grain orientation (110) surface increased the carrier mobility by 1.5 times. The practice of graphene composite coating in the isolation switch contacts has attracted attention. Raman spectroscopy analysis has confirmed that the phonon scattering cross-section of the material interface is reduced, and the temperature rise of the contact point is reduced by about 28K compared with the traditional silver plating scheme. The diamond-like carbon film prepared by plasma-enhanced chemical vapor deposition covers the outer surface of the wire-supporting tube. Its negative electron affinity characteristics significantly inhibit the corona starting voltage, and the corona loss reduction of more than 80% is achieved in an altitude of 2,000 meters. Ion implantation technology performs selective doping of metal grain boundaries, and the corrosion current density of steel U-shaped hanging rings treated with boron ion beam drops by nearly an order of magnitude.

(IV) Integration and Lightweight Technology

The topological optimization-driven structural weight reduction is reconstructing the metal tool design paradigm. The V-shaped string connection frame designed based on the finite element topological analysis results can reduce the mass by 30% while maintaining the equivalent structural stiffness. The multi-physical field coupling design integrates the drainage plate and anti-halo ring function. This integrated structure has a measured field strength distortion rate of 56% in the 220kV substation application. The internal stress distribution state of aluminum alloy overhanging wire clips produced by precision casting process combined with topological optimization algorithm is more than 30% better than that of traditional sand castings. Laser additive manufacturing technology realizes active regulation of the internal lattice structure of the metal tool, and the functional gradient material design forms a progressive intensity distribution in the anchoring area of the tension-resistant line clamp, and the fatigue life test data in this area is four times higher. The truss hollow structure of the tension-resistant wire clip of carbon fiber composite material makes the eddy current loss approach the theoretical zero point, and the weight index is only one-third of the traditional forged steel parts. The vibration monitoring of a coastal wind power transmission line shows that its resonance frequency offset is reduced by about 15Hz.

4.Application of energy-saving and consumption-reducing technology in power transmission and distribution lines

(I) Application in transmission lines

The transmission line engineering comprehensively evaluates the conductivity and environmental adaptability index of metal materials selection, and the creep-resistant high-conductance aluminum alloy tension-resistant wire clips have completely replaced the traditional forged cast iron models in heavy ice-zone lines.The wire connection parts are preferred to use the integral sleeve formed by friction stir welding process, and the internal electric field distribution of the metal tool is repeatedly corrected by the finite element calculation model to approach the ideal state.The overhang string group adopts a nonlinear damper configuration scheme, and structural dynamic analysis verifies that the design converts breeze resonance energy into heat three times more efficiently than traditional anti-vibration hammers. The acceleration sensor monitoring record of the Gobi wind field in Qinghai confirms that this strategy effectively curbs the development of conducting line bending strain.The composite insulator integrated pressure equalization ring assembly assembled at the cross-burst part of the transmission tower. The design target of this structural design is locked in a use scenario in an altitude of 3,000 meters. Multiphysics simulation shows that its surface maximum field strength is controlled within 80% of the critical corona starting threshold.The adaptive deflection mechanism of the drainage plate allows the current transmission path to maintain the contact pressure during the thermal expansion and contraction of the line. The infrared thermal image data in the high-temperature area of Guangdong show that the temperature rise of the connection point remains below the standard limit of about 35%.The concept of full life cycle guides innovation in operation and maintenance management. The drone is equipped with a metal tool temperature map collected by high-precision infrared thermal imager to construct a predictive maintenance model. The statistics of operation faults in Zhejiang power grids reflect that this technology has reduced the shutdown of the metal tool failure by nearly 40%.

(II) Application in distribution lines

The dense distribution characteristics of distribution line networks require lightweighting and weather resistance of the metal tools to be considered as priority factors. Waterproof puncture lines made of silicon-aluminum composite materials show excellent performance in coastal chemical areas.This type of wire clip body structure design integrates the concept of sealed chambers, and the electrochemical corrosion rate caused by moisture penetration is suppressed within the engineering allowable threshold range.Low-voltage branch lines generally use T-shaped groove clamps with integral die-casting. The internal pressure self-regulating module offsets the telescopic deformation of the conductor caused by seasonal temperature differences. The distribution operation and maintenance records in North China show that the frequency of loose faults of this type of metal has dropped by nearly 70%.The cable clamp of cold-shrinkage composite material equipment is used in the downline of the distribution station area. The stress memory characteristics of polymer materials provide continuous radial pressure. The long-term monitoring of Sichuan salt spray area proves that the oxidation degree of the joint remains above 90% of the new installation standard.The copper-aluminum transition terminals of the underground cable branch box adopt vacuum diffusion welding technology interface metallurgical combined state eliminates the microarc phenomenon caused by potential difference, and the Shanghai Urban Power Grid Power Quality Monitoring System detected that the background harmonic component decreased by about 30 basis points.The insulated wire connection points of the medium voltage line are designed to be covered shielding layer, and the simulation of high-frequency electromagnetic field confirms that this structure reduces the induction loss of adjacent metal components to about 35% of the original amount.The wire puncture clamp operation tool is equipped with a digital torque control system, and the installation quality traceability database shows that the optimization amplitude of the contact resistance discrete coefficient of the connection point is more than 40%.The power distribution automation transformation project adopts a functionally integrated intelligent metal system, and the wedge-shaped tension wire embedded in the micro current sensor is sandwiched in the Fujian smart distribution network to achieve automatic positioning accuracy error of the energy consumption hot spots.

Conclusion

Engineering practice has proved that the energy-saving technology of power tools needs to run through the entire chain of material selection, structural design, processing, manufacturing and operation and maintenance. Aluminum alloys and composite materials innovate the selection strategy of metal conductive dielectrics, and design optimization of hyperbolic drainage plates and other designs weaken the distortion effect of electromagnetic field distribution. The surface microarc oxidation treatment of the metal tool creates a double protective barrier, which not only maintains the body's conductive characteristics but also blocks the resistance deterioration process induced by environmental erosion. Topological weight reduction and functional integration strategies significantly reduce the energy consumption of additional loads, and lightweight components reduce the load load burden of the tower foundation structure. It is recommended that subsequent technical research and development focus on theoretical breakthroughs in designing asymmetric electromagnetic field metal tools, explore the engineering adaptation solutions of nanocrystalline metal-based composite materials, and strengthen the iteration of corrosion protection technology in coastal industrial areas. It is urgent to develop embedded perception intelligent metals in the distribution automation scenario to build a predictive control mechanism for energy consumption hotspots.

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ARTICLE

Study on the Manifestation Patterns of Rock Pressure in Transport Roadways of Downward Mining Face and Support Countermeasures

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ABSTRACT

This paper employs numerical simulation methods to conduct a systematic analysis of the surrounding rock response and stability during close-proximity coal seam down-cutting mining. Research indicates that the 5MPa vertical stress formed on the right side of the initial mining coal seam (Seam 8) significantly impacts the stability of the haulage drift. The plastic zone of the mining face rock mass is dominated by shear failure. The vertical stress at the centre of the goaf is approximately zero, while significant stress concentration occurs around the periphery. A pronounced advance support pressure zone exists ahead of the working face. During the downward mining phase, the plastic zone of the lower coal seam roadway's surrounding rock exhibited vertical expansion, with the failure mode shifting predominantly to tensile failure. A combined support scheme utilising full-section anchor cables coupled with rock bolts was proposed as the permanent support form for the haulage roadway, effectively controlling surrounding rock deformation.

1 Introduction

During downward mining of coal seam groups, the mining activity in the upper seams alters the stress state of the surrounding rock in the lower seams, thereby affecting the stability of the lower roadways. Research indicates that the key prerequisite for feasible downward mining lies in the continuity between the lower seams and the roof. Consequently, determining the depth of damage to the coal-rock strata at the floor caused by repeated mining in the upper seams holds practical significance for studies on the feasibility of downward mining in the lower seams.

Huang Qingxiang et al. [1] investigated support methods for haulage roadways affected by primary mining activities; Zhao Xiangzhuo et al. [2] examined the impact of upper coal seams on lower seam extraction, resolving roadway support issues during downward mining operations; Dai Wenxiang et al. [3] examined the layout and support methods for highly disturbed roadways during close-proximity downward mining of coal seams; Zhang Liang et al. [4] investigated the deformation failure patterns and influencing factors of dynamic pressure roadways in

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the southern wing; Fang Wanwei et al. [5] studied zone-coordinated support techniques for roadways along variable coal pillars; Li Songfeng et al. [6] investigated rock mass support techniques for roadways in extremely close-proximity coal seam downward mining;Ren Yuqi et al. [7] analysed the characteristics of floor failure under repeated downward mining of coal seam groups. The present study examines support schemes for the haulage drift of a downward mining face at the 10909 working face of a certain mine.

2 Project Overview

The 10909 working face constitutes the fifth section of the southern wing in the first mining area, specifically the 9 coal seam working face. The 10909 haulage drift has a designed strike length of 2240m, with the 10809 working face exhibiting an inclination length of 220m. The drift elevation ranges from +280.818m to +362.0m, with a burial depth of +857m to +938m. The 10809 working face directly above was mined during 2019-2020.

The 9-1 coal seam has an average thickness of 2.78m with a f-value of 1.37. The interbedded sandstone between 9-1 and 9-2 seams averages 0.76m thick, classified as semi-hard rock with an f-value of 3.62. The 9-2 seam has an average thickness of 2.63m with f=1.2. The immediate roof consists of limestone, averaging 1.2m thick, classified as a hard rock layer with f=5.46; the old roof comprises siltstone, averaging 9.75m thick, classified as a semi-hard rock layer with f=2.43; the immediate floor comprises siltstone, averaging 4.15m thick with f=3.85; The old floor comprises Coal Seam 10 and siltstone, f=3.75, with respective thicknesses of 1.67m and 15m. The 10909 working face haulage drift is being excavated directly beneath the 10809 working face haulage drift. Due to mining disturbance from Coal Seam 8, the 9 coal seam haulage drift requires reinforcement support measures.

3 Model Construction

Based on the actual geological conditions of the 10909 transport drift, a FLAC3D numerical simulation model was established. The model dimensions are: length × width × height = 180m × 224m × 80m. The 8 coal seam and 9-2 coal seam are inclined at a dip angle of 15°. As illustrated in Figure 1. Parameters were assigned to the model based on the engineering profile of the 10909 transport drift. Given the drift's burial depth of 800m, a vertical pressure of 20MPa was applied to the model's roof. The 8 coal working face was excavated first, followed by the development of the 9 coal transport drift, which was subsequently supported.

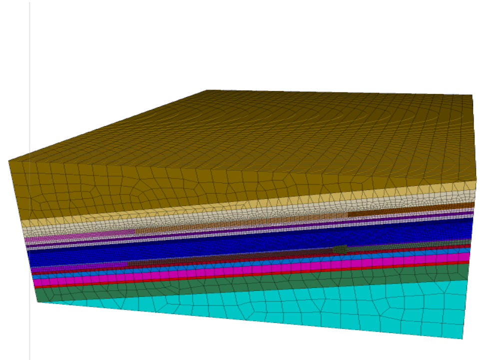

Fig. 1 Numerical Simulation Model

4 Numerical Simulation Analysis

The simulation results for the No. 8 coal seam excavation are shown in Figure 2. As evident from Figure 2, the disturbance zone generated by the 8 coal seam mining has extended to the location of the 9 coal transport drift. The mining activities disrupted the original mechanical equilibrium of the rock mass system in the 8 coal area, leaving the 8 coal seam floor exposed and causing a floor heave exceeding 10 cm. This resulted in a vertical stress concentration zone of approximately 5 MPa on the right side of the 9 coal working face, compromising the stability of the 10909 transport drift. The plastic zone formed by the 8 coal mining exhibits predominantly shear failure. The roof strata of the 8 coal seam simultaneously contain zones of shear failure and tensile failure. The tensile failure zone in the floor extends to the roof of the 9-2 coal seam and the area where the 10909 haulage drift is arranged.

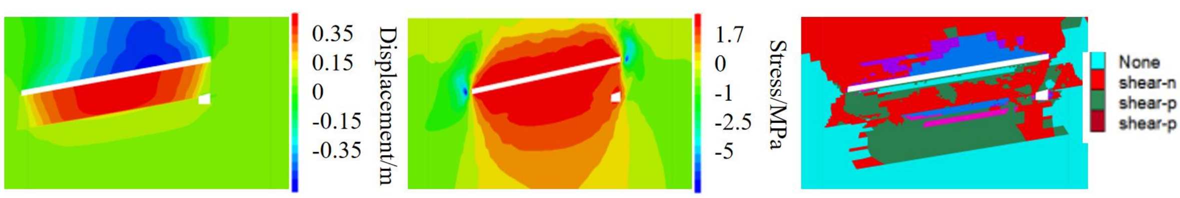

Fig. 2 Simulation Results for Coal Seam 8 Excavation

Post-extraction roof stresses in the 8th coal seam goaf, as illustrated in Figure 3. As evident from Figure 3, the entire 8th coal seam goaf collapsed post-extraction to form a pressure-relief zone. vertical stresses within the entire goaf approach zero. Conversely, significant stress concentrations occur in the roof sections interconnected with the surrounding rock mass. As the working face advances along the strike, stress concentrations around the goaf exhibit an increasing trend. The diagram indicates the presence of a high-pressure zone for advance support ahead of the working face. Consequently, the support strength for the roof in the working face must be further enhanced during mining operations.

Slicing analysis along the model trend reveals changes in the plastic zones ahead and behind the working face at excavation distances of 10m, 20m, 30m, and 40m for the No. 8 coal working face, as shown in Figure 4. As evident from Figure 4, the excavation-induced plastic zone expands significantly with increasing mining distance, primarily exhibiting substantial vertical growth. This zone initially extends vertically before undergoing minor horizontal expansion. Crucially, the plastic zones both ahead and behind the working face do not expand proportionally with mining distance and consistently manifest as shear failure. At an excavation depth of 10 metres, the plastic zones in both the roof and floor strata predominantly exhibit tensile failure. At 20 and 30 metres, the roof plastic zone shows a combination of tensile and shear failure, while the floor plastic zone predominantly exhibits shear failure. At 40 metres, the roof plastic zone again predominantly exhibits tensile failure, whereas the floor plastic zone largely shows shear failure, with a minor portion exhibiting tensile failure.

The excavation simulation results for the 10909 haulage drift are shown in Figure 5. As illustrated, the plastic zone formed after excavation of the haulage drift overlaps with that generated by the 8 coal seam excavation, thereby further expanding. The plastic zone created by the haulage drift excavation primarily exhibits tensile failure. This excavation has caused secondary disturbance to the rock mass system beneath the 8 coal seam, resulting in a broader area of stress concentration.

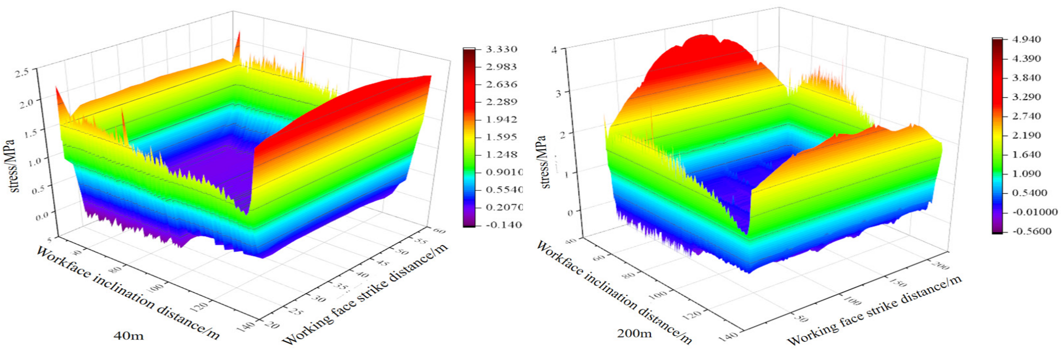

Fig. 3 Roof Stress in the Abandoned Mine Area

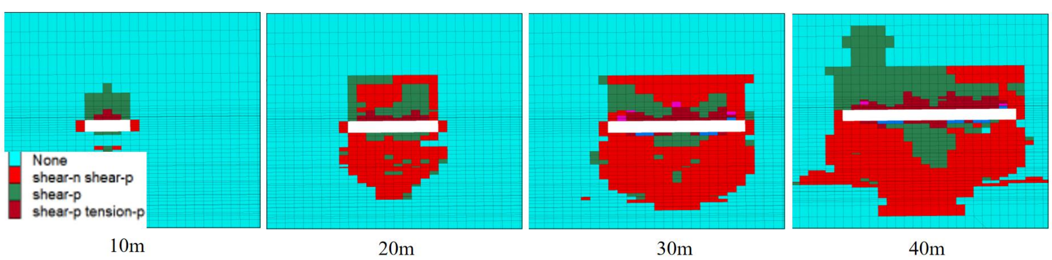

Fig. 4 Plastic zone after excavation

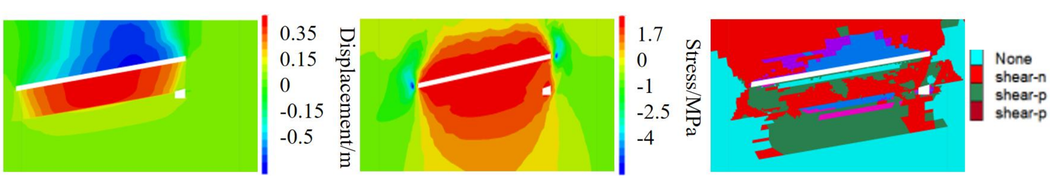

Fig. 5 Simulation Results for the 10909 Transport Longwall Face Excavation

Following the excavation of the 9th coal seam, the roof collapse in the goaf extended through to the floor of the 8th coal seam, forming an extensive pressure-relief zone, as illustrated in Figure 6. At the left-hand ventilation drift location of the working face, the roof did not fully collapse due to cantilever beam effects, resulting in a stress concentration zone. Conversely, at the right-hand 10909 haulage drift location, roof cutting interrupted force transmission within the roof, eliminating the cantilever beam effect and thus preventing the formation of a stress concentration zone.In summary, as the excavation distance increases, the plastic zone expands and the failure patterns become more complex. Consequently, more meticulous support measures must be devised during mining operations to control deformation in the roof and floor strata, thereby ensuring safe production.

5 Support Scheme for the Transport Longwall

Owing to the relatively deep burial depth and large cross-sectional area of the 10909 haulage drift, coupled with its classification as a soft rock tunnel, numerical modelling was employed to synthesise support case studies for soft rock tunnels. This determined that permanent support for this drift should adopt a combined mesh-cable support system, featuring full-section cable reinforcement with coupled cable-to-bolt support.

Anchor bolts employ Φ22×2400mm left-hand threaded steel rods, material grade MSGLW-500, with a spacing of 800×800mm, totalling 16 units; anchor bolt plates are 150×150×10mm disc-shaped iron plates, material grade Q-335; Roof cables employ Φ21.8×6300mm steel strands, while sidewall cables utilise Φ21.8×4300mm steel strands integrated with belt reinforcement for support (lower sidewall spacing adjusted to 800×1600mm). Corner anchor cables employ Φ21.8×4300mm steel strands, while floor anchor cables utilise Φ21.8×5300mm steel strands. Anchor cable spacing is 1600×2400mm, with 12 cables in total; anchor cable trays are 300×300×16mm disc-shaped steel trays; The mesh panel utilises Φ6.5 steel reinforcement mesh with a mesh size specification of 100×100mm.

Following the implementation of support measures in the transport drift, displacement in both the roof and sidewall regions markedly diminished. The stress concentration zones induced by excavation were substantially reduced, with the tensile failure zone within the plastic zone diminishing. The shear failure zone exhibited an even greater reduction relative to the tensile failure zone. Consequently, the deformation of the surrounding rock within the supported drift was effectively controlled, as illustrated in Figure 7.

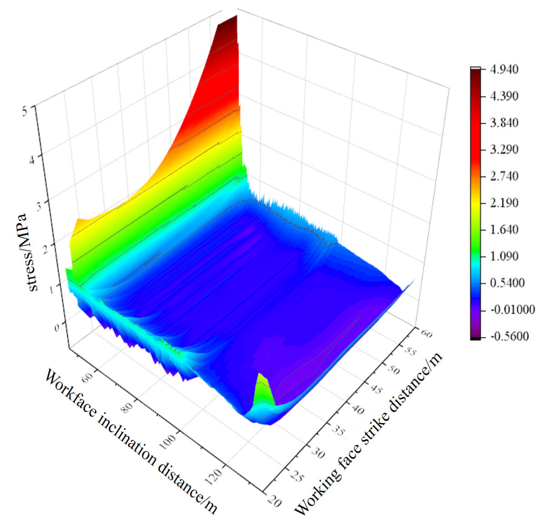

Fig. 6 Trends in Rock Mass Stress Variation

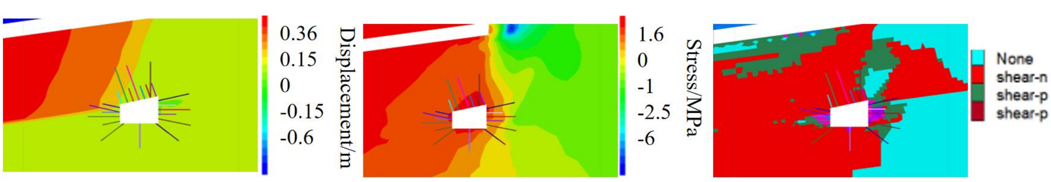

Fig. 7 Simulation Results for the 10909 Transport Longwall Support

6 Conclusions

1) Numerical simulation analysis indicates that the vertical stress on the right side of the working face is 5 MPa, affecting the stability of the haulage drift. The plastic zone formed during coal seam 8 extraction exhibits predominantly shear failure, with vertical stress in the entire goaf tending towards zero. Stress concentration around the perimeter of the mining area shows an upward trend, and a zone of high advance support pressure exists ahead of the working face.

2) During downward mining, the plastic zone in the haulage drift extends vertically, with tensile failure as the primary failure mode. This induces secondary disturbance to the coal seam 8 floor rock mass system, resulting in a broader range of stress concentration.

3) Permanent support for the drift employs a combined mesh-anchor-cable system, featuring full-section cable reinforcement coupled with anchor rods for integrated support.

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ARTICLE

The Narrative Function and Aesthetic Value of Light and Shadow Language in Modern Architectural Art

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aesthetic value

ABSTRACT

The language of light and shadow, akin to a meticulous and profound artist, outlines architectural contours with its distinctive brushstrokes, infusing buildings with vibrant vitality. Beyond being mere natural phenomena, light and shadow serve as essential narrative elements and aesthetic mediums in architectural art. They dynamically manifest multifaceted beauty through temporal shifts, seasonal variations, and angular transformations. From ancient times to the present, the utilization of light and shadow in architectural design has remained a pivotal theme for architects. In modern architecture, technological advancements and innovative design concepts have further explored and expanded their narrative functions and aesthetic values. These elements not only enhance visual impact but also guide human emotions and behaviors, creating unique spatial experiences. The perfect interplay of light, shadow, and architecture has become a striking feature in contemporary architectural art, capturing the attention of numerous architects and art enthusiasts.

As a form of spatial art, architecture's aesthetic value and narrative function cannot rely solely on static structures and materials; the use of light and shadow is equally indispensable. In modern architectural design, employing the language of light and shadow goes beyond simply utilizing natural illumination. It involves delving into the spatial and temporal dimensions of buildings. Through variations in light and shadow, architects create layered, rhythmic spatial sequences that guide visual perception and behavioral patterns, thereby enhancing the narrative quality of structures. From dawn to dusk, the flow of light and shadow on building surfaces not only records the passage of time but also infuses architecture with emotion and storytelling. Moreover, the aesthetic value of light and shadow manifests in its interaction with the building's form and materials, generating unique visual effects that amplify its artistic appeal. In contemporary architectural design, the application of light and shadow has become a crucial benchmark for evaluating artistic achievement. It not only enriches architectural expression but also provides viewers with more nuanced and diverse spatial experiences.

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1. The narrative function of light and shadow language in modern architectural art

(1) Constructing the narrative logic of architectural space

Light and shadow serve as vital expressive elements in contemporary architectural art, effectively constructing the narrative logic of spatial environments. By regulating and distributing light, they guide human movement patterns within buildings, creating rhythmic spatial experiences. The intensity and direction of illumination delineate functional zones, visually highlighting spatial hierarchy and usage attributes [1]. Simultaneously, through dynamic light variations, architectural components become interconnected—transforming isolated spatial nodes into cohesive narrative chains. This approach allows occupants to progressively comprehend the functional significance and design philosophy embedded in the space, enriching its narrative dimensions through continuous engagement.

(2) Transmit architectural emotion and cultural connotation

The language of light and shadow possesses remarkable emotional resonance, transforming architects' creative visions and architectural cultural essence into tangible visual experiences. Through the interplay of light and shadow, architects craft serene, solemn, and vibrant atmospheres that evoke emotional connections in viewers. Simultaneously, this medium serves as a cultural conduit, integrating regional heritage and historical traditions into architectural forms. By employing sophisticated lighting techniques, buildings subtly reveal their cultural depth, allowing people to perceive the cultural significance embedded in architectural designs through the dynamic interplay of light and shadow—a dual transmission of emotion and cultural heritage.

(3) Present the change of architectural time dimension

In contemporary architectural art, the interplay of light and shadow serves as a vital medium for expressing temporal variations. As the sun's position shifts and seasonal changes alter illumination angles, dynamic light patterns emerge on building facades and interior spaces. This ever-evolving interplay liberates architecture from static forms, revealing a flowing vitality that mirrors the passage of time. By observing these shifting light and shadow movements, viewers intuitively perceive the passage of time, bridging architectural spaces with natural rhythms. Moreover, the temporal transformation of light and shadow creates multifaceted architectural expressions, breaking away from rigid visual perceptions and imbuing buildings with the captivating narrative power of motion.

2. The aesthetic value of light and shadow language in modern architectural art

(1) Shaping the unique visual form of architecture

Light and shadow design is a visual art form that transforms architectural forms through the interplay of light and shadow, creating distinctive visual expressions[2]. When light interacts with building components like walls, roofs, doors, and windows, it produces dynamic interplay effects that enhance three-dimensional depth and layered perception. This interplay allows structures to showcase rich visual variations under different lighting conditions. Moreover, light and shadow can accentuate or soften specific architectural features. By skillfully manipulating light, designers can highlight design highlights while concealing formal flaws, ultimately achieving more captivating visual outcomes (as shown in Figure 1).

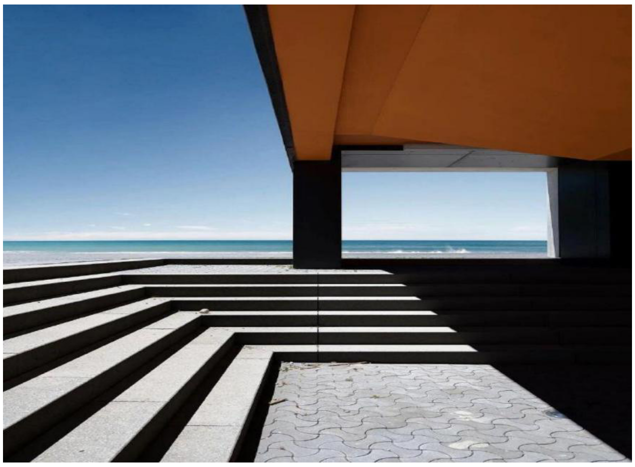

Figure 1. Schematic diagram of light and shadow forms in architecture

(2) Create an immersive aesthetic atmosphere in the building

Light and shadow form the cornerstone of architectural immersive aesthetics. By skillfully manipulating color, brightness, and spatial distribution, they create captivating atmospheres that evoke distinct moods—from warmth and mystery to openness. These carefully designed lighting schemes instantly immerse visitors in a visual realm, delivering an authentic sensory experience. Such environments not only satisfy visual aesthetics but also influence psychological states, fostering relaxation and joy within the architectural space while elevating its overall aesthetic value (Figure 2).

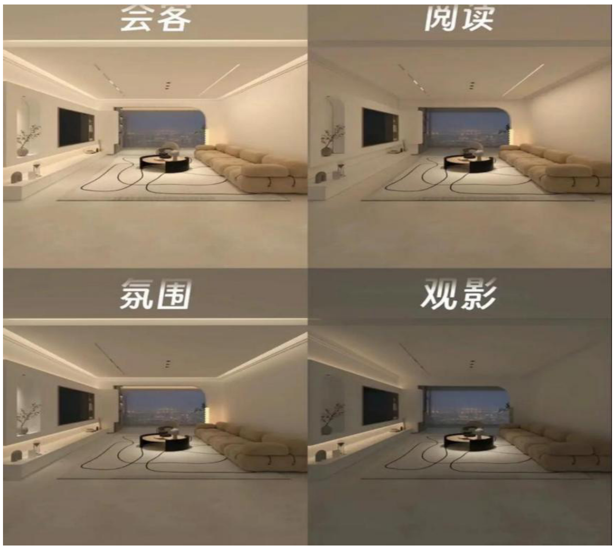

Figure 2. Schematic diagram of immersive architectural aesthetic atmosphere

(3) Constructing architectural space aesthetic hierarchy

The interplay of light and shadow can break the monotony of architectural spaces, creating rich aesthetic layers. Through contrast between illumination and shadow, blending reality with illusion, these elements divide architectural spaces into distinct visual tiers, forming a progressive relationship from near to far and from light to dark. For instance, variations in lighting can highlight key architectural features while guiding viewers' attention, with secondary areas serving as soft backgrounds. This creates a clear hierarchy in spatial aesthetics. Such layered design enhances the depth and order of architectural spaces, significantly improving their aesthetic expressiveness (Figure 3).

Figure 3 Schematic diagram of architectural space aesthetic hierarchy

3. The narrative function and aesthetic value of light and shadow language in modern architectural art

(1) Cultural venues: carrying cultural memory and artistic atmosphere with light and shadow

In architectural designs of cultural venues such as museums, art galleries, and memorial halls, the narrative function and aesthetic value of light and shadow have been deeply integrated, becoming a crucial means to convey cultural essence and create artistic ambiance. Regarding narrative functionality, designers utilize directional projection, contrast of light and shadow, and dynamic variations to construct a "spatial narrative line" based on the venue's cultural theme and exhibit content. Taking a historical museum as an example, low-intensity diffused lighting creates a solemn atmosphere that slows visitors' pace and focuses their attention on artifacts [3]. Simultaneously, directional adjustments to key exhibits highlight focal display areas, guiding viewers' gaze to historically significant pieces. Through gradual light transitions, exhibits from different eras are interconnected, allowing audiences to follow historical timelines and experience an "immersive" journey through shifting light, thereby achieving an orderly narration of historical culture.

In terms of aesthetic value, the lighting design of cultural venues emphasizes harmonious coordination with architectural forms and exhibition spaces, creating visually captivating artistic experiences. By applying the "light penetration" design concept, natural light is strategically introduced from various angles at different times of day, forming dynamic light patterns on walls and floors that continuously evolve over time, infusing static exhibition spaces with vibrant aesthetic energy. Meanwhile, through color adjustments of artificial lighting, cool-toned illumination is used in specific areas (such as contemporary art galleries) to create avant-garde abstract atmospheres, while warm-toned lighting in traditional artifact exhibition zones conveys a sense of historical warmth and depth. Through meticulous design of light color variations and contrast between illumination and shadow, each exhibition area develops its unique aesthetic identity. This approach not only meets exhibition requirements but also enhances the venue's overall artistic appeal, allowing visitors to experience cultural charm while enjoying high-quality visual aesthetics.

(2) Commercial space: Use light and shadow to guide the consumption line and stimulate the desire for experience

By leveraging the narrative function and aesthetic value of light and shadow, commercial spaces can optimize consumer experiences and enhance business appeal. From a storytelling perspective, lighting design serves dual purposes: guiding visitor flow and shaping brand narratives. Through strategic light contrasts, commercial spaces are functionally zoned. High-intensity, saturated lighting highlights flagship stores and promotional zones to attract crowds, while soft, low-intensity lighting creates leisure and transitional areas that guide orderly movement, establishing clear consumption pathways to prevent spatial disorientation. Meanwhile, brand stores utilize lighting to convey their identity. Luxury boutiques employ directional warm-toned lighting to accentuate product textures, cultivating an opulent and intimate ambiance that communicates premium positioning [4]. Young, trendy brands employ dynamic color-changing lighting synchronized with musical rhythms, creating rhythmic visual narratives that showcase brand vitality and fashion-forward energy. Through these light experiences, consumers engage with brand culture, achieving subtle storytelling through visual storytelling.

From an aesthetic perspective, the core purpose of commercial space lighting design is to “capture attention” and “stimulate experiential desires,” creating visual highlights through innovative lighting forms. In mall atriums, large-scale light installations combined with LED technology simulate dynamic light effects like starry skies and seasonal transitions, forming visually striking “check-in spots” that encourage customers to take photos and share, thereby enhancing the commercial space’s visibility. Within store interiors, the interplay between lighting and materials elevates visual depth. For instance, clothing stores use focused light on mirrors and metal accessories to create reflective effects, expanding the spatial perception. In jewelry stores, multi-angle spotlighting highlights the brilliance and cutting techniques of pieces, amplifying their aesthetic appeal.

(3) Residential community: create a comfortable atmosphere and enhance the sense of belonging with light and shadow

In residential community design (including neighborhoods, apartments, and public spaces), the narrative function and aesthetic value of light and shadow are focused on enhancing living comfort and fostering residents ‘sense of belonging. Functionally, lighting design centers on “life scene narration” by aligning with daily needs. In communal spaces like central gardens and children’s play areas, natural light and shadow variations create diverse atmospheres: morning soft sunlight invites jogging and strolls, while afternoon shade provides cool resting spots [5]. At night, low-intensity courtyard and lawn lights create a warm, safe environment while preventing eye strain from harsh illumination. Pathways are outlined with light patterns to guide safe movement, embodying the “livable and secure” community ethos. Within residential units, window orientations and balcony designs optimize natural lighting, ensuring sufficient daylight in living rooms and bedrooms while reducing reliance on artificial lighting. Curtains and blinds adjust light intensity to meet diverse needs (rest, reading, entertainment), achieving a “people-first” living scene narrative [6].

From an aesthetic perspective, the lighting design of residential areas emphasizes integration with surrounding natural environments and architectural styles, creating a harmonious and comfortable visual atmosphere. In architectural form design, light-colored facade materials are employed to enhance light reflection, giving buildings a soft and clean texture under sunlight. Through irregular balcony and bay window layouts, the facade achieves rhythmic light and shadow variations, avoiding monotonous appearances. In landscape design, the interplay between light, shadow, and vegetation creates natural beauty—such as the “light dance” between leaves forming speckled patterns on floors and walls, infusing communities with vitality. In water features, light refraction and reflection techniques produce shimmering landscapes, elevating the aesthetic quality of neighborhood scenery.

(4) Urban public buildings: Show the city’s temperament and serve public needs with light and shadow

In urban public buildings (libraries, stadiums, administrative service centers, transportation hubs, etc.), the narrative function and aesthetic value of light and shadow serve to “express urban identity” and “optimize public functions,” acting as crucial mediums for showcasing cityscapes. Regarding narrative functions, lighting design in public buildings integrates with a city’s historical culture and functional positioning to convey its characteristics and public service philosophy. For instance, the lighting design of urban libraries centers on “knowledge exploration”: During daytime, natural light filters through expansive glass facades, evenly illuminating reading areas to create bright, transparent environments symbolizing “openness and sharing of knowledge.” At night, layered interior lighting transforms bookshelf zones into warm tones while cool-colored lights outline shelves, cultivating a “serene and orderly” ambiance that guides focused reading and conveys “rigorous dedication.” Transportation hubs (high-speed rail stations, airports, etc.) adopt “efficiency and convenience” as their core narrative. High-intensity, glare-free uniform lighting ensures adequate illumination in passenger corridors, with color-coded shadows (e.g., blue for ticket-checking areas, green for transfer zones) combined with dynamic signage to guide rapid crowd flow. Large-scale light installations display cultural symbols like city landmarks and historical elements, allowing passengers to intuitively experience urban characteristics during transit while facilitating rapid cultural dissemination.

tag

In conclusion, the narrative and aesthetic value of light and shadow in contemporary architectural art holds multidimensional and profound significance. It not only enhances the spatial beauty and dynamic aesthetics of buildings, but also guides human emotions and behaviors, creating unique spatial experiences. The interplay of light and shadow enriches architectural expression while providing new perspectives and directions for modern architectural art. Looking ahead, with continuous technological advancements and innovative design concepts, the application of light and shadow will undoubtedly become more extensive and profound. There is every reason to believe that the art of light and shadow will continue to exert its unique charm, infusing contemporary architectural art with renewed vitality and creating more beautiful life experiences for humanity.

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ARTICLE

Investigation and Management of Hidden Dangers in Construction Site Safety Management

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ABSTRACT

With the vigorous development of the construction industry, various construction projects have sprung up, and the safety management of the construction site is particularly important. At the construction site, there are potential safety hazards such as falling from heights, object impact, electric shock, collapse, etc., which not only threaten the life safety of construction personnel, but also may cause delays in project progress, economic losses and adverse social impacts. Therefore, it is of great significance to systematically investigate and effectively manage the potential safety hazards on the construction site to ensure construction safety, maintain social stability, and promote the sustainable development of the construction industry.

Introduction:

Hidden danger investigation and management is the central link of construction site safety management, and hidden danger investigation refers to a comprehensive and detailed inspection of the construction site to find out various factors that may lead to safety accidents, such as improper human operation, equipment defects, poor environmental conditions, etc. This process requires professionals to use their professional knowledge and rich experience, with advanced testing technology and equipment, to inspect every link of the construction site one by one to ensure that no hidden danger is missed. The management of hidden dangers is to take effective measures to rectify and eliminate hidden dangers in response to the problems found. To achieve this, it is not only necessary for the construction unit to attach great importance to and take positive action, but also for the cooperation of the construction unit, the supervision unit and the relevant regulatory departments to form a comprehensive safety management system, so as to effectively solve the safety hazards on the construction site and create a safe and stable working en-

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vironment for the construction enterprise.

1. Analysis of the current situation of potential safety hazards on the construction site

(1) Hidden dangers of falling from heights

Falling from height is one of the most common safety accidents on the construction site, the scaffolding erection is not standardized during the construction process, the protection of the edge hole is not in place, and the operators do not use safety protection equipment correctly, and there are potential safety hazards. Scaffolding is an important support for construction workers working at height, and its construction quality is crucial to the personal safety of workers. However, in the actual construction process, some scaffolding is not constructed in strict accordance with the design and specifications, such as the pole spacing is too large, the crossbar connection is not firm, the scissor brace is insufficient, etc., these will cause the overall stability of the scaffold to be reduced, and if the external force or the improper operation of the construction personnel is encountered, it is easy to cause the scaffold to collapse or the personnel to fall accident. At the same time, the imperfect protective measures at the edge of the cave are also an important cause of falling from height accidents [1]. Many bordering areas are not equipped with guardrails or the height and strength of guardrails are insufficient; The hole is not effectively covered or not tightly covered, which is easy to cause personnel to accidentally fall when walking and working. In addition, workers who do not properly use safety equipment such as safety belts and helmets, which will also increase the risk of falling from height. If the seat belt is not properly fastened or the buckle point is not firm, it is not worn correctly or the quality is not good, which will cause effective protection for the operator during the fall process, making the consequences of the accident more serious. Due to the existence of these hidden dangers, falling accidents from heights often occur on construction sites, which poses a great threat to the life safety of workers.

(2) Hidden dangers of object strikes

The collision accident of objects at construction sites is also a common safety hazard, which is mainly caused by unstable stacking of building materials, improper operation of lifting equipment and poor protection of cross operations. At the construction site, a large number of building materials such as steel, formwork, and blocks need to be stacked temporarily, and some construction units have omissions in the management of material stacking, resulting in unstable material stacking. If the steel is piled too high, no effective anti-falling measures are taken, and the bricks stacked on the slope are not fixed, these may fall due to external forces or their own unstable center of gravity, bringing blows and injuries to the surrounding people. Hoisting equipment is an important part of building construction, once it is not properly operated, it is easy to cause accidents. In the hoisting process, the hoisting operation procedures must be strictly observed, including the bundling of hoisting items, the safety of the hoisting route, and the qualification of operators. However, in the actual operation process, there may be problems such as non-standard bundling, overloading, and no warning area in the hoisting process, which will cause the hanging object to fall and cause the object to strike the accident. In addition, cross operations often occur on the construction site, and different types of work work in the same area or on the upper and lower floors at the same time, if effective protective measures are not taken (such as setting up a safety isolation layer, delineating a safety warning area, etc.), it may also cause the upper layer of the work object to fall unexpectedly and injure the lower workers. Due to the existence of these hidden dangers, collision accidents with objects on the construction site occur frequently, which seriously threatens the life and health of construction personnel.

(3) Potential danger of electric shock

At the construction site, electric shock accidents are a very dangerous safety hazard, mainly from the non-standard installation of electrical equipment, aging and damage of wires, and illegal operation of operators. There are various electrical equipment on the construction site, such as distribution boxes, power tools, lamps, etc., and their installation and use have strict electrical safety standards. However, in the actual construction process, some electrical equipment has some problems in the installation process, such as no reliable grounding, failure of leakage protection device, insufficient distance between switch box and electrical equipment, etc. These problems can cause electrical equipment leakage, short circuits, and other faults, which in turn can lead to electric shock accidents [2]. Wires are the most important part of the power system, and its aging and damage are also a big safety hazard. The conductor at the construction site has been exposed to the complex environment for a long time, and is very susceptible to mechanical damage, wind and rain, sun exposure and other factors, resulting in damage and aging of the wire insulation layer, thus forming a conduction path between the wire and the ground or other wires, thereby increasing the risk of personal electric shock. In addition, the illegal operation of electrical equipment workers is also an important reason for the frequent occurrence of electric shock accidents. Some people do not know enough about electrical safety knowledge, and do not take necessary protective measures when using electrical equipment, such as not wearing insulating gloves, not using insulating tools, etc., or carrying out maintenance, installation and other operations without power failure, these violations will cause direct contact between staff and live parts, resulting in electric shock accidents. The existence of these hidden dangers makes the electric shock accident on the construction site always a potential safety hazard that cannot be ignored, and once an accident occurs, it often leads to major casualties and equipment damage.

(4) Hidden dangers of mechanical injury

Mechanical injury is a common safety accident on the construction site, and its main reasons are that the construction machinery protection device is not sound, the operator does not operate in accordance with the regulations, and the machinery is not properly maintained. Construction machinery such as excavators, loaders, concrete mixers, etc. are widely used in the construction site, its power, complex mechanical structure, if the protective measures are improper, it is easy to cause injuries to the operator and surrounding personnel. If the rotating parts of some machines are not equipped with protective covers or the protective covers are not installed strictly, when the equipment is running, due to the failure of the protective devices, personnel may be involved in the rotating parts, resulting in mechanical injury accidents. Operators do not operate in accordance with regulations, which is also an important cause of mechanical injury. Mechanical operation procedures are an important basis for ensuring the safe operation of equipment and personnel safety, but in the actual operation process, some operators may violate the operating procedures due to negligence, fatigue or insufficient safety awareness, such as maintenance in the operation of the equipment, failure to wear safety protective equipment correctly, lack of concentration during operation, etc., these violations will cause mechanical injury accidents. In addition, improper maintenance and maintenance of the machine also increases the risk of mechanical damage. After a long period of operation, the parts and components of mechanical equipment will gradually wear out and age, and if they are not maintained in time, their performance will be degraded or even failing. If the brake system fails and the transmission parts are loose, it may cause accidents during the operation of the equipment and cause mechanical injury accidents. Due to the existence of these hidden dangers, mechanical injury accidents often occur during the construction process, which poses a great threat to the life safety and health of construction personnel.

(5) Hidden dangers of collapse

The collapse accident is one of the most serious safety accidents on the construction site, which mainly exists in the problems of unreasonable design and non-standard construction of foundation pit excavation, formwork support system and earthwork slope. As the most basic part of construction engineering, foundation pit excavation has a very high safety risk. When the foundation pit is excavated, if the supporting structure is not selected reasonably, the slope slope is too large, which may cause the instability and collapse of the slope. At the same time, in the construction process, if the excavation is not carried out in layers and sections according to the design requirements, the support is not carried out in time, and the surrounding overload is stacked, which may lead to the collapse of the foundation pit. The formwork support system is a key component in the construction of concrete structures, and its stability directly affects the life safety of construction personnel and the quality of the project [3]. However, in the actual construction process, in the design and construction process of the formwork support system, there are problems such as excessive spacing between the support columns, the unstable connection of the crossbars, and the insufficient scissor support, which is easy to cause the formwork support system to collapse due to insufficient bearing capacity. In addition, slope instability is also an important hidden danger of landslides. Slope stability is affected by a variety of factors, such as soil properties, slope, and rainfall conditions. During construction, if the slope cannot be effectively supported and monitored, or inappropriate construction activities such as excavation and stacking are carried out near the slope, the slope will collapse. The existence of these hidden dangers makes the construction site always like a sword hanging over the head, and once it happens, it often causes major casualties and major economic losses.

Second, the construction site safety hazard investigation methods and processes

(1) Methods for investigating hidden dangers

1) Regular inspection: safety inspection of the construction site is an important part of ensuring construction safety, and choosing the appropriate inspection method is the premise of ensuring the inspection effect. Regular check-ups are one of the most basic and important check-ups, but their effectiveness is affected by many factors. When determining the periodic inspection plan, the dynamic characteristics of the construction site should be fully considered, the working environment and content of the construction site often change, and the regular in-

spection cycle is fixed, which leads to some sudden safety hazards that cannot be discovered in time. Accelerating construction or adjusting the construction process may introduce new risk points that may occur before the next periodic inspection [4]. The professionalism and sense of responsibility of the inspector is the key to the effectiveness of the inspection work, if the inspector is not professional enough, or does not pay attention to the key points of the inspection, it is possible to miss some important safety hazards. In addition, in the construction process, the setting of checkpoints should be adjusted in time according to the specific conditions of the construction site, and the safety risk points of different types of construction projects are different, and the universality and pertinence of the checkpoints need to be continuously optimized.

2) Special inspection: The special inspection is carried out for the specific type of potential safety hazards or construction stage, and its actual effect is affected by the complexity of the construction project and the refinement of safety management. There are many stages of construction of large-scale construction projects, complex processes, and many types of equipment, and special testing requires in-depth analysis of each stage and each type of hidden dangers. However, due to the complexity of engineering projects, it is difficult to do comprehensive special inspections, and some potential safety hazards may be overlooked. At the same time, special inspections are also a cross-departmental work, such as electrical safety inspections, which require the participation of multiple departments such as power engineers, safety administrators and construction workers. If there is a lack of effective communication and cooperation between various departments, the effectiveness of special inspections will be greatly reduced. In addition, with the continuous update of construction technology, new types of safety hazards will continue to emerge, and the content and methods of special testing need to be updated in time to meet new safety challenges.

3) Seasonal inspection: The implementation effect of seasonal inspection is affected by seasonal characteristics and construction adaptability, and the climatic conditions of different seasons will have different degrees of impact on the safety of the construction site, such as high temperature in summer will cause heat stroke of personnel, overheating of electrical equipment, and severe cold in winter will cause pipeline freezing and cracking and road surface icing and other safety hazards. However, the prominence of seasonal characteristics does not necessarily indicate the severity of the danger. In some regions, there is little seasonal variation, so seasonal testing may be overlooked. In addition, seasonal inspections also have a certain impact on the seasonal adaptability of construction projects. If seasonal factors are not fully considered in the design and planning stages, seasonal inspections cannot effectively detect potential safety hazards caused by seasonal changes. For example, some temporary facilities may not be reinforced or modified according to seasonal requirements, causing safety hazards in inclement weather.

4) Surprise inspection: Surprise inspection is a very random inspection method, and its implementation effect will be affected by the number of inspections, and will also affect the psychological state of construction personnel. The purpose of surprise inspections is to find out the real situation of safety management and find out the potential safety hazards, but too frequent inspections will cause resistance among employees, which will affect the construction progress and work efficiency. Conversely, if the number of inspections is too small, the deterrent effect of surprise inspections cannot be effectively exerted, and the construction unit may also relax its focus on safety during the inspection interval. In addition, the psychological state of the construction personnel also has a certain impact on the effect of the surprise inspection. If construction workers take a chance and think that surprise inspections won't happen often, they may overlook some basic safety procedures. Therefore, the relationship between the frequency and psychological counseling should be grasped in the surprise inspection of the construction site, which should not only play the role of supervision, but also not bring excessive psychological pressure to the construction personnel.

5) Instrument testing: The implementation effect of instrument testing is affected by factors such as instrument accuracy and the proficiency of testers. Professional testing equipment can accurately detect electrical equipment, harmful gases, etc. on the construction site, and its accuracy and reliability are the key to ensure the accuracy of test results. Due to the error and aging of the instrument itself, the accuracy of the test results may be reduced, so that the safety management personnel cannot correctly judge the potential hazards. In addition, the proficiency of the instrument tester also has a certain impact on the effectiveness of the instrument test, and if the tester is not familiar with the workflow of the instrument or has the wrong interpretation of the test results, it may cause safety hazards [5]. For example, when using the gas detector, if the operator does not strictly follow the operating procedures, it may cause problems such as inaccurate measurement results and failure to detect harmful gas leakage in time.

(2) Hidden danger investigation process

1) Formulate an investigation plan: Effectively carry out the investigation of potential safety hazards is an im-

portant part of ensuring construction safety. The first step of the hidden danger investigation work is to formulate an investigation plan, and its implementation effect is affected by the overall planning and resource allocation of the construction project. The overall plan of the construction project determines the objectives and scope of the investigation plan, and if the planning is not reasonable, it may lead to the deviation of the investigation plan from the actual requirements, and it is difficult to effectively cover all safety risk points. For example, construction projects may have planning deficiencies in certain high-risk areas, so that the inspection plan cannot be concentrated in these areas. In addition, whether the allocation of investigative resources is reasonable will directly affect the implementation of the effectiveness of investigative actions, and the investigation of hidden dangers is a work that requires a lot of manpower, material and financial resources, and if the allocation of resources is unreasonable, it will cause the problem that the inspection plan cannot be completed on time or the quality is not high. If there is a lack of professional inspection equipment or inspectors, the inspection work may not be carried out comprehensively.

2) Implementation of the investigation work: the hidden danger investigation is the core link of the hidden danger investigation work, and its implementation effect is affected by the complexity of the construction site and the execution of the supervisors. The complexity of the construction site is mainly reflected in the diversity of the construction process, the diversity of equipment and the mobility of personnel. These factors make verification more difficult and may lead to the possibility of missed or false detections by inspectors in the execution of inspections. For example, in the complex construction process, there may be potential safety hazards in multiple professional fields, and if the supervisors are not familiar with a certain technology, they may not be able to accurately find the hidden dangers. In addition, the implementation of the auditors also has a great impact on the effectiveness of the audit work. If the inspectors do not strictly follow the inspection plan and operating procedures, it is possible that the inspection will become a mere formality and no real safety hazards can be found. If the inspectors are perfunctory in the inspection work and do not make detailed records of the inspection points, this may cause hidden dangers to not be discovered and dealt with in a timely manner.

3) Identification and evaluation of hidden dangers: Identification and evaluation of hidden dangers is an important part of the investigation of hidden dangers, and its implementation effect mainly depends on the professional level of supervisors and the scientificity of evaluation standards. Whether the inspector can accurately find the potential safety hazards depends on the professional quality of the inspector. If the inspectors do not have sufficient professional knowledge and experience, they may mistake some non-hidden problems for safety hazards, or ignore some real safety hazards. If the inspector is not familiar with the safety standards of the electrical equipment, he may not be able to accurately determine whether the electrical equipment has leakage. At the same time, scientific evaluation criteria are also very important. If the evaluation index is not scientific and reasonable, it may lead to inaccurate hazard level and risk assessment. If the evaluation criteria are not strict enough, it is possible to underestimate some potential risks and fail to take effective measures to deal with them in a timely manner.

4) Hidden danger registration and reporting: The last step of hidden danger investigation is the registration and reporting of hidden dangers, and its effect is affected by factors such as whether the information management system is perfect and the responsibility implementation mechanism. Hidden danger registration refers to the need for detailed records of the discovered danger points, including information such as the location, type, and severity of the danger points [6]. If the information management system is not perfect, it may cause problems such as inaccurate and incomplete registration of hidden dangers, which will affect the follow-up management of hidden dangers. For example, manual entry is prone to errors, omissions and other problems. At the same time, the accountability mechanism has a great impact on the effectiveness of accident registration and reporting. If the responsibility is not clear, it may cause the hidden danger can not be reported in time or no one is responsible, such as the inspector can not report to the superior in time after discovering the hidden danger, and can not deal with the hidden danger in time.

3. Management strategies for potential safety hazards on construction sites

(1) Personnel level

People are the core variable in construction safety management, and people's safety literacy directly affects the treatment effect of hidden dangers. The establishment of a systematic safety education and training system should be carried out in accordance with the logic of stages and levels. When new employees enter the company, they will first conduct 3-5 days of pre-job safety training, and in strict accordance with the requirements of the GB50656 "Safety Production Management Specifications for Construction Enterprises", adopt modular teaching methods, and standardize the explanation of safety regulations, the demonstration of basic operating procedures, and the use of personal protective equipment. The virtual safety experience device is used to simulate typical accident scenarios such as high falls and electric shocks, supplemented by theoretical explanations, to strengthen the safety risk awareness of new employees. Training and assessment of the implementation of the "double standard" system, the theoretical score must reach 85 points, the practical examination requires independent completion of five basic operations, such as scaffolding foundation construction, the correct use of fire extinguishers, etc., do not meet the standard to re-train, until qualified.

Carry out continuous skill improvement training for in-service employees, and conduct special training on a quarterly basis according to the project progress as the timeline. In the first month of each quarter, the project security department organizes the technical department to formulate a targeted training plan for the key points of the current quarter (such as the construction of the formwork support system during the construction of the main structure and the safety of the hanging basket operation during decoration). The training adopts a combination of "theoretical teaching, on-site practice and online assessment", invites industry experts to explain theoretical knowledge, organizes on-site practical guidance for technical backbones, and uses the online learning platform to consolidate exercises and assessments after class. Implement an annual retraining system for special operation personnel, requiring them to participate in more than 40 hours of professional skills renewal training, and participate in the special operation qualification review examination organized by the provincial housing and urban-rural development department.

The cultivation of managers' safety management ability needs to establish a three-in-one talent training system of "theory-practice-innovation". 2-3 senior seminars on safety management are held every year, including cutting-edge management theories such as risk matrix analysis methods and safety culture construction models; Organize management personnel to regularly participate in safety management exchange activities of cross-project to learn advanced management experience; Managers are encouraged to conduct research on safety management innovation topics, and individuals who propose effective improvement plans are commended [7]. Establish a safety performance evaluation mechanism for managers, and incorporate 10 indicators such as the incidence rate of safety accidents and the rectification rate of hidden dangers into the annual assessment system, and directly link them with promotion and personal performance.

(2) Equipment level

The safe operation of construction machinery and equipment depends on the fine management of the whole process, and in the process of equipment procurement, a standardized process of "technical demand analysis - supplier screening - contract signing - entry acceptance" has been established. Before procurement, the technical department, together with the equipment management department, formulates a detailed technical requirement document in accordance with the equipment configuration plan in the construction organization design, and gives a detailed description of the performance parameters, safety standards, and energy consumption indicators of the equipment. Suppliers are screened through the method of "pre-qualification, on-site inspection, and comprehensive scoring", focusing on the supplier's production license, quality certification system and after-sales service capabilities, and establishing a directory of qualified suppliers. When signing the contract, it is necessary to clarify the core elements of the equipment, such as technical parameters, acceptance standards, warranty terms, etc., and establish a performance bond system.

The equipment entry acceptance implements the "three-level inspection" system, and the equipment management department first checks the appearance and data of the equipment to ensure that the equipment model and random documents meet the provisions of the contract. The operating parameters of the equipment are tested by professionals in the no-load test. Finally, the safety of the special equipment is inspected by a third-party testing agency, an electronic acceptance file is established during acceptance, and the acceptance data and image data are uploaded to the mobile terminal in real time, and the unqualified equipment is returned within 24 hours.

Establish a three-level maintenance system of "daily spot inspection, regular maintenance, and special maintenance", formulate equipment maintenance standard manuals, and clarify the maintenance cycle, maintenance items and technical requirements of each equipment. The daily spot check is carried out by the operator before the start of each shift, and the key parts of the equipment are checked one by one by using the check table, and the abnormalities are reported in time; The professional maintenance team conducts regular maintenance every quarter, comprehensively inspects, lubricates, calibrates, and conducts special maintenance on equipment that has been in use for more than 3 years or more than 5,000 hours, and entrusts a professional organization to evaluate the performance and fault diagnosis of the system. Build an equipment maintenance management information system to realize the automatic push of maintenance plans, update maintenance records in real time, intelligently analyze maintenance costs, use big data algorithms to predict the failure cycle of equipment, and formulate preventive maintenance plans in advance.

The method of "dynamic evaluation-hierarchical disposal-orderly update" is used to manage the old equipment. According to the four dimensions of equipment service life, maintenance cost, potential safety hazards and technological advancement, an equipment evaluation index system is established, and a quantitative scoring model is established. An expert review is organized every six months, and the evaluation results are divided into three levels: "scrapped", "technological transformation" and "eliminated within a time limit". For the equipment that needs to be technically transformed, the technical department should work with the supplier to formulate a transformation plan, and implement it after expert demonstration; For equipment that has been eliminated within a limited time, establish disposal records, and standardize the scrapping and transfer procedures of equipment.

(3) Environmental aspects

The environmental optimization of the construction site needs to be systematically studied from three dimensions: layout planning, operation condition improvement and extreme weather response. In the site layout planning stage, a 3D model of the site is established based on BIM technology, and the construction process is dynamically optimized. The safety passage is planned in accordance with the principle of "double channel and double exit", the width of the main passage is not less than 4 meters, the road surface is hardened, continuous protective railings are set up, and emergency lighting is set every 50 meters. The material stacking area implements the "five determinations" (fixed area, fixed variety, quantity, identification and responsible person), and steel, wood and other materials are stacked according to the specifications to establish a stable stacking rack; There should be a special warehouse for flammable and explosive materials, and there should be fire and explosion-proof facilities. The division of the operation area follows the principle of "concentration of the same kind and convergence of processes", and a movable fence is set up to achieve physical isolation between areas and reduce mutual interference between operations [8]. Review and adjust the site layout every quarter according to the construction progress to ensure that the overall layout meets the requirements of safety and construction. The governance mode of "source governance-process governance-effect monitoring" is adopted to govern the operating environment. An intelligent spray dust reduction system is installed in the earthwork area, and the dust concentration is monitored in real time by using PM2.5/inhalable particulate matter sensors, and the sprinkler device is automatically activated. The method of combining "noise cancellation, sound insulation, and sound absorption" is adopted to install sound insulation covers on high-noise equipment such as concrete mixers, and prefabricated noise barriers are installed around the construction site, and low-noise construction techniques (such as hydraulic crushing instead of mechanical crushing) are adopted. Ventilation management refers to the use of axial fans to implement mechanical ventilation in special places such as underground engineering and confined spaces, and is equipped with gas detectors to monitor the concentration of oxygen and harmful gases in real time, and when the concentration exceeds a certain value, an alarm will be automatically issued to start the emergency ventilation system. Set up an environmental monitoring station to detect 6 indicators of the operating environment every day, such as dust, noise, temperature, humidity, etc., and upload them to the environmental management platform in real time.

(4) Management level

The optimization of the safety management system is carried out in accordance with the PDCA cycle mode of "system design, implementation monitoring, and continuous improvement". In the system construction stage, in accordance with the guiding ideology of the "Work Safety Law of the People's Republic of China", combined with the actual situation of the enterprise, a safety management manual is formulated, including 12 core systems such as "safety responsibility system", "safety inspection system" and "hidden danger management system". The safety production responsibility system adopts the form of "post safety responsibility system list", implements safety responsibility to each post, and makes detailed provisions on the content, assessment standards and accountability methods of responsibility. Establish a three-level inspection system of "daily inspection, special inspection, and comprehensive inspection", formulate an inspection standard table, and make detailed provisions on the inspection methods, judgment standards and rectification requirements for each inspection content. The hidden danger management system implements three levels of management of "red, yellow and blue", of which the red hidden danger is rectified within 24 hours, the yellow hidden danger is rectified within 3 days, and the blue hidden danger is included in the monthly rectification plan.

Establish a full-chain management mechanism of "discovery-disposal-acceptance-review", in the intelligent inspection system, inspectors can use their mobile phones to scan the QR code, they can record the hidden danger information, and then the system automatically generates hidden danger work orders and pushes them to relevant personnel. During the rectification period, the relevant personnel need to upload the rectification plan, rectification photos and other process data to the system, and the safety management department will use the geographic information system to monitor the rectification and improvement in real time. After the rectification is completed, the acceptance team will accept the site in accordance with the acceptance specifications, and the system will complete the acceptance confirmation, establish a hidden danger review mechanism, conduct monthly statistics and analysis of the rectified hidden dangers, use fishbone diagrams, Pareto diagrams and other tools to find high-frequency hidden dangers and management loopholes, and put forward targeted improvement measures.

The structure of "data acquisition-intelligent analysis-dynamic control" is used to build an information management platform, and the Internet of Things technology is used to build an intelligent sensor network to monitor the construction site (such as tower cranes, deep foundation pits, temporary power distribution boxes, etc.) in real time. On this basis, a big data analysis platform for security management is developed, and machine learning algorithms are used to mine data in depth, build a risk early warning model, and realize 72-hour early warning of security risks. Establish a three-dimensional visualization management system with information model-GIS integration, realize the association of hidden danger information, surveillance video and other information with the three-dimensional model, and realize the visualization of hidden danger location and dynamic display of dangerous status. On the mobile APP, the whole process of safety management business is handled online, and managers can view the list of hidden dangers, issue rectification instructions, and approve safety documents at any time, so as to truly achieve the intelligence, refinement and high efficiency of safety management.

Fourth, case analysis of hidden danger investigation and treatment in construction site safety management

(1) Case background

A super high-rise commercial complex with a total height of 300 meters and a construction area of more than 250,000 square meters, with more than 1,500 on-site staff during the peak construction period, involving civil engineering, mechanical and electrical, curtain wall and other professional cross construction. In the early stage of construction, due to the tight construction period, difficult management and coordination, etc., many potential safety hazards appeared in the construction process. The wall parts of the scaffold are unreasonable, and some parts are not installed in accordance with the requirements of the specification; Temporary power lines are generally privately pulled and connected, and leakage protectors are not installed in distribution boxes; Lack of operation records of large-scale equipment such as tower cranes and other large-scale equipment, and untimely maintenance; The monitoring frequency of deep foundation pit is insufficient, and there is a small displacement phenomenon in the surrounding soil. At the same time, the safety awareness of construction workers is poor, illegal operations occur from time to time, and safety management is facing a severe test.

(2) Implementation process

The project leadership team quickly set up a special rectification team for potential safety hazards and formulated a comprehensive investigation and remediation plan. In terms of hidden danger investigation, a combination of regular inspection and special inspection is adopted to carry out special inspections on key parts such as scaffolding, temporary electricity, and large equipment. BIM technology is used to model the construction process, simulate the construction process, and identify potential safety hazards in advance. For the potential safety hazards discovered, strictly implement the "red, yellow and blue" hierarchical management, and clarify the person responsible for rectification and the time limit for rectification. In the process of remediation, overall reinforcement measures were taken to re-standardize the setting of connecting wall components; Replace temporary power lines in a unified manner, install intelligent distribution boxes, and realize real-time leakage monitoring; Establish the life cycle management file of the tower crane and entrust it to a professional organization for its maintenance; Add deep foundation pit monitoring points and carry out 24-hour real-time monitoring. At the same time, strengthen the safety education and training of employees, organize virtual reality experiences through daily safety morning shifts, and enhance the safety awareness of employees.

(3) Implementation effects

After three months of special rectification, the level of project safety management has been significantly improved. 326 hidden dangers were investigated and rectified, with a rectification rate of 100% and no safety accidents. The number of construction workers' violations has decreased by 85%, and the pass rate of safety knowledge examinations has increased from 60% to 95%; The use of information management means to carry out real-time monitoring and dynamic control of potential safety hazards on the construction site, so that the safety management efficiency is increased by more than 40%. In the later stage of the project, it successfully passed the acceptance of the provincial safe and civilized construction site, and the experience of safety hazard investigation and treatment was promoted in the local construction industry, which provided guarantee for the smooth implementation of the project and also improved the social reputation and market competitiveness of the enterprise.

epilogue

To sum up, the investigation and treatment of potential safety hazards on the construction site is of great significance to ensure the life safety of construction personnel, ensure the quality of the project, and promote the healthy development of the construction industry. In the future, with the progress of science and technology and the continuous improvement of safety management level, the safety hazards of construction sites will become more and more intelligent and refined. The use of advanced information technology, automation equipment and strict safety management standards can significantly improve the safety level of the construction site, lay a solid foundation for the high-quality development of the construction industry, and promote the stable and harmonious development of society.

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ARTICLE

Smart Maintenance Technology and Its Application for Subgrade Frost Heave Diseases on Roads in Cold Regions

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ABSTRACT

Roads in cold regions are often affected by frost heave, resulting in structural damage such as cracking, uplift, and subsidence, which seriously undermines road stability and traffic safety. Traditional maintenance methods, characterized by delayed response and low efficiency, are inadequate for the complex and dynamic nature of frost heave in these regions. This study begins with an analysis of the mechanisms and distribution of frost heave-related subgrade diseases, examining how frost heave deteriorates road performance and identifying the limitations of current maintenance techniques. In response, this paper introduces the concept of "smart maintenance" enabled by advances in information technology and intelligent sensing. Key components of smart maintenance—including multi-source monitoring, data analysis, predictive modeling, and intelligent decision-making—are explored to develop a refined, data-driven, and automated maintenance management system. Through case studies, the paper validates the technical advantages and practical effectiveness of smart maintenance in predictive interventions, structural regulation, and disaster early warning. The findings suggest that smart maintenance significantly improves efficiency, reduces operational costs, and extends service life of roads in cold regions, thus demonstrating strong application potential.

1. Introduction

The frequent occurrence of seasonal frost heave in cold regions poses a major threat to the performance and structural safety of road infrastructure. As road networks expand in northern and high-altitude regions of China, frost heave-related diseases have become increasingly severe, characterized by high frequency, persistence, and concealment. These issues not only raise maintenance costs but also compromise road service quality and safety.

Conventional road maintenance practices, relying primarily on manual inspections and reactive repairs, suffer from delayed responses and lack the capacity for timely risk control in the face of sudden or structural damage

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caused by frost heave. In light of this, the integration of smart technologies in road maintenance has emerged as a promising solution. The rise of the Internet of Things (IoT), remote sensing, big data analytics, and intelligent algorithms has enabled the construction of maintenance systems capable of real-time monitoring, trend forecasting, and dynamic intervention.

This paper focuses on the characteristics and impacts of subgrade frost heave diseases in cold regions, explores the architecture and core technologies of smart maintenance systems, and analyzes their application in real-world scenarios. The objective is to provide theoretical guidance and practical insights for sustainable road maintenance in cold climates.

2. Causes and Characteristics of Frost Heave Diseases in Cold Region Roadbeds

The formation of frost heave diseases in road subgrades is influenced by climate fluctuations, hydrological conditions, soil types, and construction quality. During the freezing season, moisture within the subgrade freezes and expands, creating upward pressure that leads to surface uplift and cracking. When thawing occurs, the melted layer loses bearing capacity, resulting in surface deformation and subsidence. The repetition of this freeze-thaw cycle accumulates internal stresses, threatening the long-term stability of the road structure.

Frost heave is especially prevalent in fine-grained soils such as silt and clay, which exhibit high water content and capillary action conducive to ice formation. Drastic temperature variations are a major exacerbating factor; in northern China, winter temperatures often fall below -30°C, with frost depths exceeding 2 meters. Inadequate drainage systems, insufficient compaction, and improper construction timing further aggravate frost-related damages.

Common manifestations include longitudinal cracks, surface bulges, and localized depressions. In severe cases, frost lenses may form, leading to structural displacement and reduced surface smoothness, ultimately compromising driving safety. These damages are cyclical and cumulative; without timely intervention, they can escalate rapidly, underscoring the necessity for accurate identification and effective treatment.

3. Limitations of Traditional Maintenance Approaches

In current practice, maintenance of cold-region roads is largely dependent on manual inspections and reactive repair strategies. While these methods provide basic remediation, they fall short in responsiveness and precision, particularly when dealing with complex frost heave phenomena. Specific limitations include:

Delayed Detection: Reliance on visual inspection and vehicle-mounted sensors makes it difficult to identify latent or early-stage structural damage. By the time surface deformation is observed, internal frost damage may already be severe, missing the optimal intervention window.

Limited Data Utilization: A lack of systematic data collection and historical analysis results in arbitrary maintenance decisions. Repair actions are often experience-driven and lack the support of a lifecycle-based maintenance strategy.

Simple Technical Means: Traditional repair techniques—such as cold patching, refilling, or partial reconstruction—are ineffective against deep-layer frost damage or structural instability. Harsh winter conditions further hinder timely repair operations.

Fragmented Management: Maintenance responsibilities are often distributed among various agencies, leading to communication gaps, long response times, and inefficient resource allocation.

To overcome these challenges, there is a pressing need for a smart, technology-driven maintenance system capable of proactive identification, precise intervention, and dynamic risk management.

4. Architecture and Key Technologies of Smart Maintenance Systems

Smart maintenance systems integrate sensing, communication, data analytics, and intelligent control technologies to establish a closed-loop management platform encompassing monitoring, analysis, decision-making, and execution. The system includes the following components:

(1) Multi-Source Sensing and Data Acquisition

Sensors—including ground temperature probes, soil moisture sensors, strain gauges, fiber-optic temperature cables, LiDAR, and UAV-based photogrammetry—are deployed to capture real-time data on subgrade temperature, moisture, structural deformation, and environmental changes. The fusion of diverse data sources enhances monitoring accuracy and provides a robust foundation for analysis.

(2) Big Data Platform and Disease Analysis Models

Utilizing edge computing and cloud platforms, massive sensor datasets are processed, cleaned, and analyzed. Advanced algorithms such as data mining, time-series forecasting, and AI-driven modeling enable trend analysis and risk prediction of frost-related diseases. Comparison with historical data allows for rapid diagnosis of recurring issues.

(3) Intelligent Warning and Response Mechanisms

Based on a multi-index evaluation framework, early warning models are developed with tiered alert thresholds. Once abnormalities are detected, the system automatically triggers alerts and pushes notifications to management platforms and maintenance crews, ensuring prompt intervention and improved hazard preparedness.

(4) Smart Decision-Making and Maintenance Optimization

After locating and assessing the severity of frost heave damage, the system recommends optimal intervention strategies, matching resources and repair methods accordingly. Maintenance plans are dynamically adjusted based on weather conditions, resource availability, and traffic control constraints, enhancing scientific planning and operational flexibility.

The adoption of smart maintenance transforms management from experience-based to data-driven, providing a powerful tool for addressing frost-related challenges in cold-region roads.

5. Practical Applications of Smart Maintenance in Cold Regions

Several pilot projects in Heilongjiang, Inner Mongolia, and Xinjiang have implemented smart maintenance systems in highways, national roads, and municipal streets, yielding positive outcomes.

In one case, a provincial highway integrated a frost heave risk monitoring system using soil temperature and moisture sensors, fiber-optic cables, and UAV patrols to monitor high-risk segments. Real-time analysis enabled early detection of subgrade bulging, allowing maintenance crews to preemptively conduct layered grouting and insulation sealing, preventing large-scale cracking.

Another project utilized automated laser scanning and 3D reconstruction to assess post-thaw deformation across a highway. Historical monitoring data supported the development of a frost heave evolution model, facilitating the identification of high-risk zones and precise targeting of maintenance resources. The results showed a 40% reduction in response time, 60% increase in repair efficiency, and a 30% decrease in annual maintenance costs.

Nonetheless, challenges remain, such as inadequate cold resistance of sensors, unstable data transmission in extreme temperatures, and high integration costs. Future improvements should focus on optimizing hardware resilience, lowering deployment costs through modular designs, and enhancing overall system robustness and adaptability.

6. Conclusion

Frost heave-induced subgrade diseases in cold-region roads present a formidable challenge due to their complexity, hidden nature, and rapid progression. Traditional reactive maintenance models are no longer sufficient. Smart maintenance technologies—powered by sensor networks, big data, predictive modeling, and intelligent decision-making—offer a proactive, efficient, and cost-effective alternative.

This paper analyzes the mechanism of frost heave, outlines the limitations of conventional maintenance, and proposes a smart maintenance system tailored to the needs of cold-region roads. Real-world applications demonstrate significant improvements in efficiency, accuracy, and resource utilization.

To realize the full potential of smart maintenance, further efforts are needed to standardize system components, enhance integration with BIM/CIM platforms, and establish coordinated management frameworks. In parallel, research should focus on adapting technologies to extreme climates and improving system durability. With continued innovation and policy support, smart maintenance will play an increasingly vital role in ensuring the resilience and sustainability of road infrastructure in cold regions.

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ARTICLE

Construction Technology of Self-Anchored Suspension Bridges

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ABSTRACT

As a special type of building, the industrialization of bridges is imperative in the context of the new industrialization era. The specific focus of bridge industrialization is to promote prefabricated construction technology in bridge construction. Based on the construction experience of the Dongta Bridge spanning the Hun River in Shenyang City, this article summarizes the construction techniques of prefabricated segmental assembled piers, continuous steel box girders, steel truss bridge towers, cables, and steel bridge deck paving for self anchored suspension bridges, providing experience for similar bridge construction in the future.

1. Project Overview

The Dongta Bridge over the Hun River in Shenyang is a key project in the comprehensive improvement plan of "one river and two banks" in Shenyang. It is the largest single span suspension bridge in the Shenyang area and has been put into use, becoming a local landmark building. The operation diagram of the Dongta Bridge over the Hun River in Shenyang is shown in Figure 1. The main bridge of Dongta Bridge over Hunhe River in Shenyang City is a five span continuous steel truss bridge tower self anchored suspension bridge, with a span arrangement of (40+90+220+90+40) m and a total steel consumption of 20000 tons.

Figure 1 Operation diagram of Dongta Bridge over Hun River in Shenyang City

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1) The main beam is a continuous steel box girder spanning the Hun River, with a width of 43.3m in the cable area and 40m in the non cable area. The beam height in the cable area is 3m, the beam height in the counterweight area is 2.3m, and the beam height in the anchorage area is 4.8m. The steel beam section size is large, and reasonable segmentation, transportation, and hoisting are the key points;

2)The main tower adopts a combination of steel truss tower columns and concrete tower bases. The tower height above the bridge deck is 45m, and the horizontal distance between the center of the main tower and the bridge is 36m. The main tower is composed of a bridge tower concrete tower base, steel truss tower columns, tower top saddle covers, tower top decorative structures, and tower top crossbeams from bottom to top. The tower base is a concrete structure, while the steel truss tower columns, tower top saddle covers, tower top decorations, and tower top crossbeams are all steel structures.

3)The main cable is composed of high-strength galvanized steel wire, with a total of two cables installed throughout the bridge, with a vertical span ratio of 1/5.5 and a center to center distance of 36m in the transverse direction. Each main cable consists of 19 strands, with a single strand consisting of 127 high-strength galvanized steel wires with a diameter of 5.0mm. The amount of steel wire used is 331t, and the diameter of the main cable in the cable clamp is 271mm. The suspension cables are made of epoxy coated steel strands, with a total of 74 cables installed throughout the bridge. The construction of the main cable is a key process of this bridge. How to ensure that the bridge shape and internal stress of each component of the suspension bridge meet the design requirements, as well as the system transformation, is the focus of the cable system construction of the suspension bridge.

4) The steel bridge deck pavement adopts the pouring asphalt pavement technology, with a pavement structure of 41mm high elastic modified asphalt (SMA13) upper layer+30mm pouring asphalt mixture (GA10) lower layer+methyl acrylic resin (MMA) waterproof bonding layer. The pouring asphalt pavement of the steel bridge deck is a special process of this project, and ensuring the quality of the bridge deck pavement is the key;

5) Some bridge piers are assembled using prefabricated segments, with a solid cross-section of 2×2m, a height of 7.5m, and a single weight of 80t. This is the first of its kind in the Northeast region of China. The construction of prefabricated bridge piers belongs to a new technology, and the connection between piers and abutments adopts grouting sleeve connection. The construction process is complex and the construction difficulty is high.

2. Construction technology of prefabricated self anchored suspension bridge

2.1 Prefabricated segmental assembly bridge pier construction technology

Prefabricated segmental assembly of bridge piers, as the name suggests, means that the piers are prefabricated first and then installed on the construction site. Its main construction consists of two sections: prefabrication and assembly.

2.1.1 Prefabrication construction technology for bridge piers

The prefabrication of bridge piers includes steps such as the construction of prefabricated pedestals, the production and installation of steel cages, the installation of overall formwork, concrete pouring, curing, and formwork removal. Here, only the prefabrication of a single pier body is illustrated to illustrate the prefabrication process:

1) Prefabricated pedestal production. Make three prefabricated pedestals on the hardened site near the bridge pier, requiring a flat and open site.

2) Steel cage production. The reinforcement of the pier body is cut, reinforced, and formed in the reinforcement processing yard, and together with the grouting sleeve, it is tied onto the frame to form a complete reinforcement cage.

3) Steel cage hoisting. After the steel cage is made, it will be installed. The steel cage is installed on the prefabricated pedestal using a four point lifting method using a car crane. At the lifting point of the steel cage, reinforced angle steel is added. In addition, the steel cage is connected to the prefabricated pedestal operating frame to ensure the stability of the steel skeleton.

4) Installation of overall template. On the site near the prefabricated pedestal, the formwork is assembled into a whole using a truck crane and fitted onto the installed steel cage. Then, fine adjustments are made to ensure the verticality of the formwork and the joint gap. After passing the inspection, double-sided tape is used to seal the joint between the templates, and sponge strips are used to seal the gap between the prefabricated pedestal bottom plate and the pier body template to prevent leakage of grout. And connect the template with the prefabricated pedestal operation frame to ensure the stability of the steel reinforcement skeleton.

5) Concrete pouring, curing, and formwork removal. The pouring is done in one go. Before pouring, check the position of the steel bars, formwork, and steel bar pro-

tection layer, and adjust any areas that do not meet the requirements. During the pouring process, the concrete should be vibrated and compacted uniformly at all times. After the concrete pouring is completed, the exposed surface of the concrete should be tightly covered and watered for curing in a timely manner. When the concrete strength of the pier body reaches 2.5MPa, the formwork can be removed.

2.1.2 Bridge pier assembly construction technology

After the prefabrication of the bridge pier is completed, a large tonnage crane is used for on-site assembly. The assembly of the bridge pier includes steps such as the construction of the grouting layer, the hoisting and positioning of the pier body, and the grouting of the sleeve. Here, only the assembly of a single pier body is illustrated to explain the assembly process:

1) Construction of the grout layer. Firstly, remove cement slurry, thin film, loose sand and gravel, oil stains and other debris from the support platform and surface of the steel bars in the connection area. Then, install a grout stop ring on the connection steel bars to prevent grout from entering the sleeve during grouting. At the same time, make a grout stop template. Pour the slurry into the slurry area.

2) Lift the pier body into place. Before the slurry solidifies, a large tonnage crane is used to lift the pier body from the prefabricated pedestal to the bearing platform for installation, and the plane position of the pier body is adjusted. In addition, use precision adjustment devices and mechanical jacks to adjust the verticality and elevation of the pier body. When the slurry reaches the required strength, remove the mechanical jack and fine adjustment device, as shown in Figure 2.

3) Sleeve grouting construction. The grouting equipment adopts a pressure grouting machine, and the grouting material adopts high-strength non shrinkage cement grouting material. Sleeve grouting mainly includes slurry preparation and grouting. To ensure dense grouting, clean the debris inside the sleeve with clean water before grouting, and then pour the mixed grout into the grouting machine to start grouting. After grouting is completed, maintenance should be carried out. During the maintenance period, the pier body should not be disturbed by earthquakes, collisions, or other impacts.

2.2 Construction technology of continuous steel box girder

The continuous steel box girder is erected using the bracket method. The steel box girder is divided into sections according to the module, processed into lifting unit blocks in the processing plant, and transported to the site for lifting and welding.

Figure 2 Pier body lifting diagram

2.2.1 Division technology of steel box girder segments

In order to reduce the circumferential joint of the beam segments and facilitate the installation, the standard section of the main bridge is vertically divided and integrated by a length of 12 meters, which is an integer multiple of the spacing between partitions of 3 meters. After the division, the longitudinal beam segments are changed from the original design of 53 beam segments to 43 beam segments, and the horizontal segments are divided into 10 unit blocks between the top and bottom plate U ribs; The original H, G, and F sections of the self anchored special section are divided into upper and lower layers. The upper layer is equipped with plate units and delivered to the site, and the bridge position is assembled separately. The lower layer is lifted horizontally in blocks according to the standard beam segment segmentation scheme; During the assembly and manufacturing of the box body in the beam section, temporary tie rods and dowels are used to connect the horizontal segments of each beam section. When hoisting the steel box girder unit block, bolt lifting ears are used.The longitudinal steel beams are assembled as a whole on both the north and south banks every 4 sections in the factory, with the middle section serving as the closure section. The steel beams are processed and manufactured in a total of 11 rounds. After each round of steel beam production is completed, they are shipped and lifted at any time according to the on-site lifting plan requirements.

2.2.2 Steel box girder segment lifting technology

The steel box girder is installed using a large tonnage crane, and is installed from the north and south banks towards the middle of the main bridge span. The main steps are as follows:

1) Island construction. Consider building islands within the river channel, taking into account the space for transporting beams and crane stations. The elevation of the island construction is 2 meters higher than the normal water level, and the width of the island construction is twice the width of the steel beam. Local areas will be widened, and a drainage channel will be reserved in the main river channel. Temporary supports will be set up on the entire island construction surface. When the steel box girder is erected in the drainage area of the main river channel, the completed side span area will be excavated and diverted, and the reserved drainage channel will be filled with soil for island construction. The steel box girder unit blocks are directly transported to the bridge site by flatbed trucks in the factory, and lifted on the island surface by crawler cranes. The large section steel beams are segmented and directly lifted on the island surface.

2) Lifting and alignment. After lifting the unit block into place, measure the centerline, elevation, and diagonal difference between the sections of the bridge, adjust the deviation in a timely manner, and then level the joints in the order of web plate → top plate → bottom plate. When leveling, it is advisable to first level the corners of the box mouth with high rigidity (web plate and bottom plate corners, web plate and top plate corners), and then fix the remaining parts to ensure that the misalignment of the joint plate surface is not greater than 1.0mm. After welding the positioning plate, loosen the hook, and weld according to the welding requirements of the bridge position after loosening the hook, as shown in Figure 3.

Figure 3 Hoisting diagram of steel box girder

2.2.3 Steel box girder closure technology

When the steel beams are erected to the closure section, all the steel beams on both sides of the north and south banks are welded. The dimensions and elevation between the closure openings are repeatedly measured during fixed time periods in the morning, middle, and evening, and the measurement time temperature is recorded. Finally, the closure temperature and dimensions are analyzed and determined, and the dimensions are fed back to the processing plant to process the steel box girder of the closure section. The appropriate temperature is selected, and the steel box girder closure section is installed to achieve the closure of the steel box girder.

2.3 Construction technology of steel truss bridge tower

When making the steel truss bridge tower, it is divided into five sections from bottom to top along the height direction, including GT1-GT5, with a length of 6m to 12m. Among them, GT1 has a height of 6m and is a steel-concrete joint section of the tower column. In addition, the top beam of the tower is divided into three sections for hoisting.

During installation, GT1~GT5, bridge tower saddle cover, crossbeam and other components are installed in sequence. When installing GT1 and GT2 steel tower columns, the crane lifts them on the island surface. When installing GT3~GT5 and crossbeam, the crane lifts them on the steel bridge deck. Steel plate supports are used at the crane lifting station to protect the steel structure bridge deck, as shown in Figure 4. Considering the installation accuracy of steel tower columns, matching parts are used for connection during the production of steel tower columns to ensure the construction accuracy on site.

Figure 4: Main Tower Lifting Diagram

2.4 Cable construction technology

The main cable is constructed using the prefabricated parallel steel wire strand method (PPWS). During the installation, the direct traction method is used to first install a three span continuous catwalk. After the steel box girder is closed, single line reciprocating traction systems are arranged on both sides of the catwalk, and unit cable strands and other cable strands are installed. The tower top cable strands are horizontally moved into the saddle, anchored with north-south locks, tightened, and the catwalk system is converted. The main cable unit cable strand installation adopts single line reciprocating traction, with one set of traction system arranged upstream and downstream.

2.4.1 Installation and construction of catwalk

The overall structure of the catwalk adopts a three span continuous structure, parallel to the main cable's empty cable shape, with a distance of 1.2m from the center of the main cable. The net width of the catwalk is 3.0m, and both ends are anchored to the top surface of the box girder. To increase the wind resistance stability of the catwalk, two transverse overpasses and eight wind resistant vibration control cables are set up in the mid span catwalk, and four wind resistant cables are set up on each side span. The catwalk is composed of load-bearing cables, crossbeams, surface mesh, handrails, handrail ropes, safety ropes, horizontal overpasses, wind resistant cables, and other structures. Install the load-bearing cable anchorage end distribution beam → symmetrically install the catwalk load-bearing cable one by one → adjust the load-bearing cable line shape → install the handrail cable and railing → install the wind resistant cable → inspect and accept the catwalk.

2.4.2 Construction of Traction System

The function of the traction system is to lift the anchor end of the unit cable over obstacles. The main process flow is as follows: Install the main cable tugboat on the catwalk crossbeam → Install the saddle slide at the top rod hole of the main cable saddle to allow the cable strands to pass through the main cable saddle smoothly → Adjust the tower top suspension structure, place the steel rails on both sides horizontally, and use them as anchor end bearing cables at the vertical support points of the tower top → Erect the anchor end bearing cables, with a height of about 3.0m from the catwalk, anchored at both ends to the anchor beam → Install the main traction cable, auxiliary traction cable, open pulley, etc. on the catwalk → Debug the system operation status.

2.4.3 Benchmark Cable Installation

The main steps of benchmark cable construction include cable traction, shaping, saddle insertion, anchor head insertion, and linear adjustment.

1) Rope traction. Use a winch to pull and unfold the anchor head of the unit cable strand from the cable reel to the starting end of the catwalk, then pass the cable strand through two tower tops to reach the anchor box position on the other side, and make a mark on the main cable strand to place the unit cable strand reasonably.

2) Plastic surgery and saddle insertion. After the cable is pulled in place, use a square fixture to organize the cable from a regular hexagon into a square shape in a stress free state, and then move the cable horizontally into the saddle.

3) Anchor head into anchor. After the cable is inserted into the saddle, the anchor begins to step into the anchor. After the anchor head is anchored, the traction work of the next cable strand begins.

4) Linear adjustment. The adjustment of stock demand is generally based on the principle of first mid span and then mid span. Specifically divided into initial adjustments during the day and precise adjustments at night. There is a significant temperature difference during the day, so according to calculations, adjust the cable strands to a controlled height at an appropriate temperature; The temperature difference at night is small, so according to the calculation, adjust the cable strand accurately to the control height.

2.4.4 Ordinary cable installation

The common strand shall be erected according to the erection process of the benchmark strand, but the alignment of the common strand shall be controlled by relative deflection and sag, that is, by referring to the alignment of the benchmark strand, supplemented by a special caliper, the strand erected on the previous day shall be adjusted before the temperature rises significantly in the morning every day. For each layer of cable, the height of the cable should be half a strand higher than that of the next layer. The two layers of cable that directly overlap should be kept in a flexible state, slightly higher by 0-5 mm, and should not press down on the lower layer of cable. After all cable strands are erected, check the height of all cable strands and make overall adjustments to those with significant deviations until they meet the requirements.

2.4.5 Cable tightening

Tightening cables are divided into two parts: pre tensioning cables and formal tensioning cables. Tightening the cable first starts from the mid span towards the top of the two towers, and when it is about 50m away from the top of the tower, it starts from the top downwards; At the edge span, it is only necessary to move from the bridge surface to the top of the tower. It is agreed to change the direction from the top of the tower to the bottom when it is about 50m away from the top of the tower. Pre tensioning cable is to compress the hexagonal strands in situ into a circular shape through a pre tensioning cable machine; When formally tightening the cable, use a cable tightening machine to round the main cable and achieve the specified void ratio. The quality of the tight cable is controlled by the void ratio and roundness.

2.4.6 Cable clamp installation

After the main cable is tightened, install the cable clamp. The installation of cable clamps uses a hanging basket as the working platform, and the lifting is carried out by a steamship crane. The difficulty in installing cable clamps is the tightening of cable clamp bolts, which is carried out in two stages. When installing the cable clamp in place, use a wrench to pre tighten it, and then use a torque wrench to firmly fasten it for the first time. After the suspension cable is loaded, use a torque wrench to tighten it for the second time. The installation sequence of cable clamps is from the mid span to the top of the tower, and from the vicinity of the anchoring point to the top of the tower for the side spans. After the installation of the cable clamp is completed, proceed with the installation of the suspension rod.

2.4.7 System Conversion

System conversion is the process of installing and tensioning suspension cables. Before installing the sling, calculate the optimal loading program based on the stiffness and self weight of the main beam and cable. And during the construction process, adjust the tension force.

Temporary working support feet and connecting rods are required for the tensioning of slings. Eight through hole jacks are used for symmetrical tensioning from the tower column and anchor head. During homework, the connecting rod is connected to the internal thread of the anchor cup at the bottom of the sling, and the sling is fixed to the anchor plate through the anchor cup. Apply 1/4 of the design force during the first tensioning to temporarily lock each sling; Apply the full design force to tension the suspension cables for the second time, then check the actual load of each suspension cable, and finally make specific adjustments to each suspension rod based on the design force. During the tensioning process of the suspension cable, based on actual observation and calculation analysis, the saddle is pushed upwards. After repeating this process, the tensioning force of each suspension cable is adjusted to the design value.

2.5 Construction Technology for Steel Bridge Deck Pavement

2.5.1 Sandblasting and Waterproofing Construction of Bridge Deck

After the installation of the steel box girder is completed, the bridge deck pavement will be carried out. The foundation of bridge deck paving is sandblasting of steel bridge deck. Sandblasting mainly uses sandblasting machines, and for the vertical parts of edges and road edges that cannot be reached by sandblasting machines, manual sandblasting is used. Before operating the sandblasting machine, manual sandblasting must be completed first. After the sandblasting of the steel bridge deck is completed, it is necessary to form a continuous flow of work with the waterproof construction, that is, to timely apply the waterproof primer to avoid exposure for more than the specified time.

After the construction of the steel bridge deck primer is completed, the spraying construction of the waterproof layer begins. Before spraying construction, wrap the structures at the construction boundary with plastic film for protection to prevent waterproof materials from splashing onto them and causing pollution. After the construction of the waterproof layer, the construction of the bonding layer shall be carried out.

2.5.2 Construction of poured asphalt

Cast asphalt is a self forming asphalt that does not require rolling. It is transported using a cooler truck with heating and mixing devices, and spread using a dedicated asphalt paver, as shown in Figures 5 and 6.

Figure 5 Cooker car

Figure 6 Special pouring asphalt paver

Based on the structural characteristics of asphalt pavers, a 60-150cm wide edge strip is reserved for manual paving during pouring asphalt paving, while dedicated pavers are used for paving in other areas. Spread the edge strip before mechanical paving. During mechanical paving, after the pouring asphalt self mixing plant discharges the material, it is transported to the construction site by a cooler truck and continuously spread throughout the bridge from one end to the other using a paver. After pouring asphalt paving, timely spread asphalt pre mixed crushed stone and embed it into the surface of the pouring asphalt mixture. Apply joint strips at the joints and boundaries of the pouring paving to ensure that the joints are tight and leak proof.

2.5.3 Surface layer SMA asphalt mixture construction

SMA asphalt mixture is spread using a dual machine joint paving method, completing half the width of the bridge in one paving. When paving, the distance between the two machines should not exceed 10 meters, and the roller should be organized to compact the SMA asphalt mixture on the steel bridge deck according to the principle of "closely following, slow rolling, high frequency, and low amplitude". The surface layer SMA paving and leveling adopts non-contact balanced beam automatic leveling to ensure that the flatness meets the requirements.

3. Conclusion

In response to the construction of the Dongta Cross Hun River Bridge in Shenyang, the new technology of prefabricated segment assembly, continuous steel box girder erection construction, steel truss bridge tower construction, cable construction, and steel bridge deck paving were adopted to solve the problems of prefabricated bridge piers, wide section steel box girders, large tonnage steel truss bridge towers, main cables, and steel bridge deck paving. This project was completed quickly, safely, and efficiently, and has a good reference value for similar engineering constructions. The successful application of prefabricated segmental assembled bridge piers in this project is of great significance for promoting the transformation of concrete bridge piers from conventional cast-in-place technology to factory prefabricated technology in the special environment of the north.

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ARTICLE

Pathways and Practices for Improving the Durability of Engineering Materials under Extreme Plateau Climate Conditions

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ABSTRACT

This paper addresses the durability issues of engineering materials under extreme plateau climate conditions, using a bridge on the Qinghai–Tibet Railway as a case study, and investigates methods and practices to enhance the durability of engineering materials. Through multi-scale material modification, structural-construction synergistic optimisation, and the establishment of an intelligent monitoring platform, practical application tests were conducted in engineering projects. The results show that the concrete spalling area was reduced by 82%, the rebar corrosion rate decreased to 1.1%, and the coating chalking grade stabilised at level I; the full lifecycle maintenance costs dropped by 46%, and the net present value increased by 130 million yuan. Therefore, the proposed methods for improving the durability of engineering materials can significantly enhance material durability, providing effective solutions for plateau engineering.

Introduction:

Extreme climatic conditions in plateau regions, such as very low temperatures, large temperature differences, frequent freeze-thaw cycles and strong ultraviolet radiation, pose severe challenges to the durability of engineering materials. Infrastructure such as the Qinghai-Tibet Railway, located at an altitude of 4800 m, faces issues like concrete spalling, low-temperature brittle fracture of steel and coating powdering, resulting in high maintenance costs and shortened service life. Existing studies mostly focus on single material improvements, lacking systematic approaches and engineering practice verification. This study aims to fill this gap by integrating materials science, structural engineering and intelligent monitoring technologies to propose a comprehensive enhancement plan. Its significance lies in ensuring the safe operation of plateau engineering, reducing whole-life cycle costs, supporting major national infrastructure construction, and providing technical references for similar extreme environments. Background analysis shows that parameters such as 250 freeze-thaw cycles per year and a temperature difference

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of 90 °C accelerate material degradation, necessitating innovative strategies to address the climate-load coupling effect.

1.Project Overview

1.1 Characteristics of Plateau Extreme Climate and Engineering Challenges

The K1151 320 Super Bridge on the Qinghai-Tibet Railway is located on the northern slope of the Tanggula Mountains at an altitude of 4,800 m, in a typical extremely cold plateau region. Continuous records from the on-site automatic weather station over three years show that the bridge site experiences extreme low temperatures of -40°C, an annual temperature difference of 90°C, ultraviolet radiation intensity 1.3 times that of the plains, 250 annual freeze-thaw cycles, peak wind speeds of 28 m/s, and frequent sudden changes in wind direction. To quantify the coupled effects of multiple factors, a climate-load coupling matrix was constructed. Six variables—temperature, humidity, radiation, wind load, salt spray and traffic vibration—were synchronously collected on an hourly scale. Pearson correlation analysis showed that the correlation coefficient among the temperature-radiation-freeze-thaw three factors reached 0.82, confirming it as the dominant driving chain. Under the influence of this chain, the depth of concrete surface spalling is exponentially related to the number of freeze-thaw cycles, the impact toughness of steel at -40°C decreases by 38%, and the grade of coating powdering rapidly progresses from grade I to III, forming three major core damages.

1.2 Research on the Current Status and Durability Failure of Engineering Materials

To systematically understand the degradation patterns of engineering materials after 10 years of service on the plateau, 120 core sampling points were arranged in the main bridge span, piers, and bearing areas of the K1151 320 Super Bridge, with a core diameter of 100 mm, penetrating from the protective layer to the rebar interface. After vacuum drying, the specimens were scanned using X-CT at a voxel resolution of 5 μm to reconstruct the three-dimensional pore network, revealing that freeze-thaw cracks were layered parallel to the exposed surface, with frequencies of 42%, 35%, and 23% in the 0–5 mm, 5–10 mm, and 10–15 mm depth intervals, respectively, and crack density decayed exponentially with depth. SEM observation showed that the crack walls were covered with ettringite and ice crystal impressions; EDS surface scanning confirmed that the Ca/Si ratio decreased from 1.82 to 1.35, indicating ongoing decalcification of C-S-H[1]. Concurrently, standard Charpy V-notch specimens were taken from the stiffening ribs and main chords of the bridge, and compared with pre-operation baseline data, the mean impact toughness at -40 °C decreased from 142 J to 88 J, a reduction of 38%, with a fracture fibre rate of less than 20%, showing a typical cleavage morphology. For coatings, a handheld spectrophotometer was used to measure 30 points each on the deck, web, and bottom plate, with areas of gloss loss ≥60% accounting for 57% of the total area. Pulverisation levels were assessed according to ISO 4628-6, with grade III and above accounting for 44%. Integrating macroscopic defects and microscopic damage, a four-level failure classification was established: Level I for minor visual discoloration, Level II for visible cracks ≤0.1 mm, Level III for cracks 0.1–0.3 mm wide with gloss loss >30%, and Level IV for cracks >0.3 mm or coating exposure. The statistical results are shown in Table 1, with Level III and IV combined accounting for 48%, indicating that the plateau bridge materials are generally in a moderate to highly degraded stage, requiring priority interventions targeting freeze-thaw crack propagation and low-temperature embrittlement of steel.

Table 1 Statistical Table of Failure Levels of Major Materials in Plateau Bridges

Failure Level	Concrete crack depth/mm	Impact energy reduction rate of steel/%	Coating Dullness Rate/%	Sample Proportion/%
Level I Minor	0–2	<10	<20	18
Level II Moderate	2–5	10–25	20–40	34
Significant at level III	5–10	25–40	40–70	31
Level IV failure	>10	>40	>70	17

2.Design of Durability Enhancement Pathways

2.1 Multi-scale Material Modification Technical Route

A multi-scale synergistic modification technology system is proposed to address material degradation mechanisms under extreme plateau climates. The concrete is modified using a ternary composite of nano-SiO_2, rubber powder, and paraffin/silica phase-change microcapsules. Nano-SiO_2 reduces capillary porosity through the pozzolanic effect, rubber powder with an elastic modulus of 1.8 MPa mitigates frost expansion stress, and the microcapsules suppress temperature fluctuations in the -5 ℃–10 ℃ range[2]. The synergy of the three reduces the 56-day chloride ion diffusion coefficient to 1.7×10^{-12} m^2/s, a reduction of 55%. The steel selected is Q420qENH low-alloy steel, which after quenching and tempering (QT) treatment attains a dual-phase microstructure of lath martensite and reversed austenite, followed by chemical plating to form a 25 μm thick Ni-10P amorphous coating. This composite structure achieves an impact energy of 120 J at -40 ℃, a 36% increase compared with conventional Q345 steel. The coating system uses hydroxyl fluorosilicone resin crosslinked with HDI trimer curing agent, with nano-CeO_2 added as a UV shield; after 1000 h of QUV accelerated ageing, the colour difference ΔE≤1.5 and adhesion maintains at 12 MPa.

To quantify the transport behaviour of chloride ions under freeze-thaw cycles, a temperature fluctuation correction term is introduced based on Fick's second law.

$$\frac{\partial C}{\partial t} = D_{eff} \cdot \nabla^2 C + \alpha \cdot \frac{dT}{dt}$$

Here, C represents the chloride ion concentration (unit: mol/m^3), Deff is the effective diffusion coefficient (unit: m^2/s), α is the temperature gradient influence factor (unit: $m^2\cdot K/mol$), T is the temperature (unit: °C), and t is the time (unit: s). This model considers the effect of microcrack propagation caused by water phase change during the freeze-thaw process and characterises the acceleration of ion transport by cracks through the α value (0.08–0.15).

2.2 Structure-Construction Collaborative Optimisation Strategy

At the structural-constructive synergistic optimisation level, a three-tier protection system is implemented to address plateau frost heave, frost expansion, and low-temperature brittle fracture issues. A 5 cm thick superhydrophobic protective layer is sprayed on the surface of concrete components using a methyl silicate-based composite slurry (contact angle 158°), effectively inhibiting frost-thaw spalling by lowering the freezing point by 3.5°C and blocking capillary water absorption paths (water absorption rate ≤1.5%). The bearing system is designed as a replaceable neoprene bearing (hardness 60 IRHD) with a built-in lead-core damper with an energy dissipation coefficient of 0.25, and double-layer stainless steel sliding plates are set to reduce the friction coefficient to 0.03, achieving dual control of seismic and thermal deformation. The foundation frost heave resistance uses an "outer steel pipe-concrete composite pile" structure, with a 600 mm outer diameter steel pipe wall thickness of 12 mm, filled with C60 micro-expansive concrete, and a 2 mm thick paraffin-based frost heave buffer layer between the steel pipe and frozen soil, controlling frost heave displacement within 3 mm/year. Key welds undergo 100% TOFD (time-of-flight diffraction) and phased array ultrasonic combined testing. Weld excess height is mechanically ground to below 0.5 mm, and ultrasonic impact treatment is used to introduce residual compressive stress of 210 MPa, reducing the stress concentration factor to 1.8.

2.3 Intelligent Monitoring and Life Prediction Platform

To establish a full life-cycle durability management closed loop, 72 embedded intelligent sensor nodes were deployed at key parts of the K1151 320 Superbridge, including MEMS temperature and humidity sensors (accuracy ±0.3 ℃), solid-state chloride ion sensors, and fibre Bragg grating strain sensors. Data is transmitted to an edge computing gateway via LoRa self-organising network, aligned with timestamps and cleansed of anomalies before being uploaded to the cloud platform, forming a four-layer architecture of 'sensing-transmission-cloud-evaluation'. The sensing layer collects environmental and response parameters at 5-minute intervals; the transmission layer uses a star-mesh hybrid topology with a packet loss rate of <0.1%; the cloud platform layer establishes a material degradation feature database; the evaluation layer achieves condition diagnostics by integrating physical mechanisms with data-driven models[3].

Durability reliability degradation model coupled with Monte Carlo stochastic simulation and Gamma process:

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \times \prod_{i=1}^{n} \Phi\left(\frac{\ln C_{th} - \mu_{\ln C_i}(t)}{\sigma_{\ln C_i}}\right)$$

Here, Rt represents the reliability index at time t, η is the scale parameter (unit: years), β is the shape parameter, Cth is the material failure threshold (unit: e.g., chloride ion concentration mol/m^3), μ lnCit represents the logarithmic mean function of the i-th degradation quantity, σ lnCi is its standard deviation, and Φ· is the standard normal distribution function. This model characterises the discreteness of the degradation process through the β value (1.2–2.5), and μ lnCit is dynamically updated using sensor data to achieve Bayesian probabilistic prediction of the remaining service life.

3.Engineering Practice and Effect Verification

3.1 Implementation of Demonstration Sections and Construction Quality Control

Within the demonstration section ranging from K1151 320 to K1152 180 over 860 m, material replacement and structural optimisation were carried out separately for bridge spans, pier bodies, and bearing areas. The concrete used the previously mentioned ternary synergistic modified mix, and an on-site forced mixing station was equipped with a cooling water system with an accuracy of 0.4 °C to ensure the discharge temperature did not exceed 10 °C. Before pumping, air content loss was reduced using a decompression plate, resulting in a measured air content of 5.2 %, meeting the control range of 5 ± 0.5 %. Steel components, after QT treatment and chemical plating in the factory, underwent acid-free sandblasting activation; on-site bolt splicing rate reached ≥85 %, and the remaining circumferential welds were 100 % re-examined using TOFD phased array in accordance with ISO 17640, with defect echo amplitudes >20 % DAC being rejected and repaired[4]. A summary of key quality control indices is shown in Table 2, with a 28-day concrete compressive strength average of 68 MPa, chloride ion diffusion coefficient of 1.6×10^{-12} m²/s, steel -40 °C impact energy of 121 J, and coating adhesion of 12.3 MPa, all within the upper limit of the specifications, providing a consistent foundation for subsequent long-term service performance.

Table 2 Summary of Key Quality Control Indicators for the Demonstration Section

Control project	Regulatory requirements	Measured average	Standard deviation	Pass rate/%
Air content of concrete/%	5 ± 0.5	5.2	0.18	100
28 d compressive strength/MPa	≥60	68	2.1	100
Chloride ion diffusion coefficient/(10^{-12} m²/s)	≤2.0	1.6	0.09	100
Impact energy of steel/J	≥100	121	4.5	100
Coating Thickness / μm	50 ± 5	51	1.7	98
Coating adhesion/MPa	≥10	12.3	0.6	100

3.2 On-site Long-term Monitoring and Performance Comparison

The demonstration section has been inspected continuously for 36 months from the time of delivery in parallel with the untreated control section. Each quarter, high-resolution imaging by drone and manual grid checks were used to obtain surface deterioration information. The area of concrete spalling decreased from an average of 8.7% in the control section to 1.6%, a reduction of 82%; the corrosion current density of the reinforcing steel measured by linear polarisation showed a decrease in corrosion rate from 8.4% to 1.1%, and the anodic polarisation resistance increased by an order of magnitude[5]. The coating chalking grade evaluated according to ISO 4628-6 indicated that 44% of the control section was level III or higher, while the demonstration section remained stable at level I, with gloss loss decreasing from 62% to 18%. Accelerated freeze-thaw cycle tests were carried out simultaneously for 300 cycles; the relative dynamic elastic modulus retention of the specimens was ≥95%, whereas the control section specimens of the same batch fell below 60% after 180 cycles, significantly postponing the performance degradation inflection point. The comparative results are shown in Figures 1 and 2.

3.3 Economic Benefits and Prospects for Promotion

Based on a 30-year full life cycle cost model, the initial additional investment for the demonstration section is 9.8 %, mainly due to the premium of nano-modified concrete, QT plated steel, and fluorosilicone coating; however, maintenance costs decrease by 46 %, benefiting from reduced painting and reinforcement frequency due to lower rates of spalling and corrosion. At a 5 % discount rate, the net present value increases by 130 million yuan, and the investment payback period is shortened to the 12th year. As of 2024, five bridges on the Qinghai-Tibet line from Golmud to Lhasa and the Sichuan-Tibet line from Ya'an to Nyingchi have applied this technology, with a cumulative application length of 42 km and altitudes ranging from 4300 to 4800 m, forming a replicable and promotable paradigm for enhancing durability in extreme environments, providing both technical reserve and economic benefit for the subsequent construction of the plateau railway network.

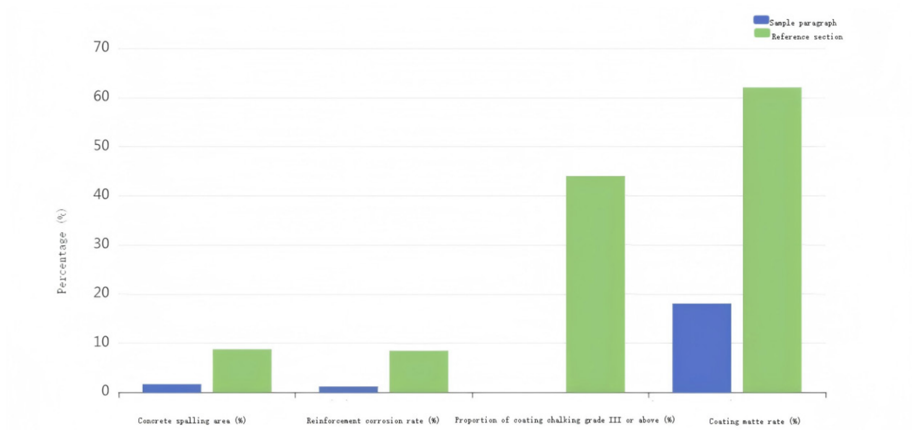

Figure 1: Bar chart comparing the key performance indicators of the demonstration section and the control section

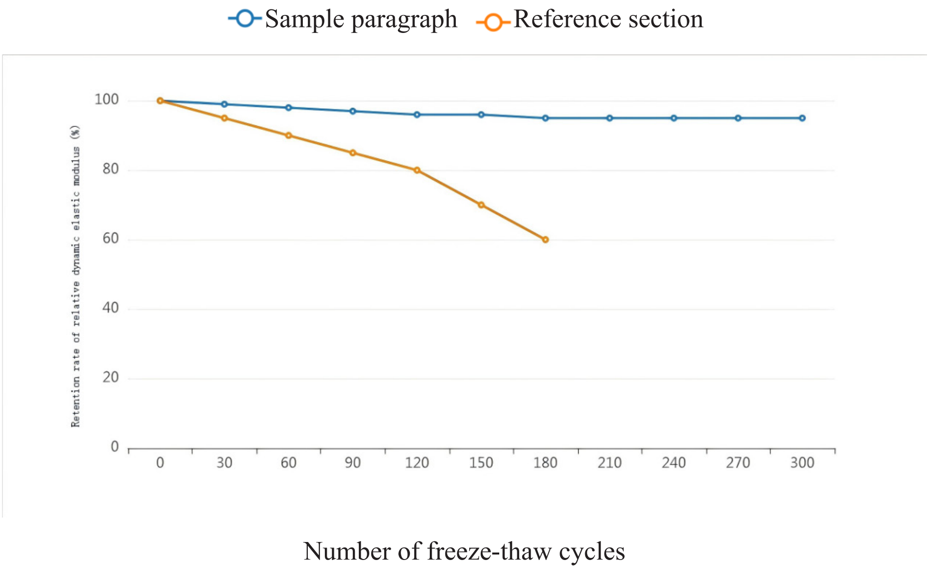

Figure 2: Freeze-thaw cycle - Relative dynamic elastic modulus decay curve

Conclusion:

In summary, this study systematically verified the effectiveness of pathways to enhance the durability of engineering materials under extreme plateau climates. Through practical demonstration sections, it successfully achieved optimisation of material performance and long-term stability. Innovatively, it proposed ternary synergistic modified concrete, composite treated steel and fluorosilicon coating systems, combined with structural optimisation and intelligent monitoring, significantly inhibiting freeze-thaw crack propagation and low-temperature embrittlement. Future work should deepen research on the microscopic mechanisms of materials, extend to higher altitude areas, and explore the application of artificial intelligence in lifespan prediction. This pathway lays a foundation for the sustainable development of plateau engineering and contributes to the implementation of major national strategies.

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