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Fine-grained Applications of BIM Technology in the Whole Life Cycle of Green Buildings Based on Case Analysis

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Abstract: Against the backdrop of the global decline in environmental resources, in response to the national call for environmental protection, green buildings have gradually become the core of the construction industry's development. As a digital technology that has been continuously innovated in recent years, Building Information Modeling (BIM) technology has played a significant role in many green building projects. This paper, based on the application of Building Information Modeling technology and the requirements of green buildings, combines specific cases to analyze the application of Building Information Modeling technology in each stage of the green building's life cycle and the changes it has brought. The results show that compared with traditional construction methods, Building Information Modeling technology, with its advantages of greater refinement, visualization, and data-driven approach, has had a significant impact on reducing resource and energy consumption in building construction while meeting industry standards and human needs.

Keywords: Building information modeling technology; The entire life cycle; Green buildings; Energy consumption

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1. Introduction

1.1. The concept of building information modeling technology

Building Information Modeling is a building model established based on various relevant information data for construction projects. Through digital information simulation, BIM technology can simulate the actual information of a building [1,2]. The technology integrates building information and various performance data; based on designer requirements, BIM technology conducts evolution analysis of different schemes and generates visualized building models for the decision-making evaluation of construction plans. Throughout the entire life cycle of green buildings, BIM technology can effectively simulate building rationality, comfort, resource utilization, and energy consumption. This process forms decision-making plans that comply with building standards, meet occupant needs, and achieve the most efficient use of environmental resources with the minimum energy consumption.

1.2. Advantages of building information modeling technology

Traditional building projects have long relied on hand-drawn sketches, manually collected data and human-based analyses. This invites calculation errors, slows information exchange among stakeholders, delays communication, and drags out later-stage corrections. The introduction of BIM eases these pain-points in several ways.

(1) For visualization

As a digital technology, BIM translates qualitative green-building targets into measurable data and 3D models. Computers, not people, run the analyses, cutting the risk of error. The three-dimensional, visual model lets designers spot problems immediately and adjust the design on the spot.

(2) For collaboration

BIM provides a single platform where all parties can work together. Design files are pushed to the platform instead of being passed manually, eliminating transfer lag and the data losses that often accompany it.

(3) For energy optimization

The digital model allows precise control of indoor ventilation, daylight penetration and airflow pattern. Coupled with environmental-psychology principles, this yields a minimum-energy configuration [3].

(4) For quantity take-off reliability

Engineering quantities calculated with BIM are also highly reliable. In 2018 Liang Wang et al. studied quantity-information exchange and reuse on a media-tower project. Comparing Revit and GCL models, they exported the Revit model to GCL through IFC and GFC formats. Graphic-element conversion hit 100%, and the quantity deviation from the standard dropped below 1%. Their conclusion: for a civil-engineering Revit model, importing GFC-format data into Glodon BIM-based quantity-taking software gives a dependable take-off workflow [4].

(5) With the improvement of BIM efficiency, labor costs and material costs can be reduced, reducing costs in many aspects.

1.3. Green-building life-cycle

A "green building" is one that still meets all code requirements while cutting environmental resource use, optimizing the allocation of social resources such as labor, and lowering energy demand, ultimately reducing ecological impact and providing a healthy place for people to live and work. The life-cycle of a building spans its entire existence, from cradle to re-use: planning and design, construction, operation and maintenance, and demolition and recycling. The green-building life-cycle takes these four stages and injects concrete green-building targets into each one, producing an optimized, fully integrated life-cycle [5,6].

2. Green building whole-life-cycle: Planning and design, construction, operation and maintenance, and demolition & recycling

2.1. Planning and design

A green building must minimize environmental impact, so as shown in **Figure 1**, on Project planning and feasibility: targets should focus on energy-use optimization and efficient allocation of resources (materials, equipment, labor) while assessing global effects on both environment and occupants. Site selection and analysis: Choose locations after detailed surveys of topography, geomorphology, soil, and hydrology; let the natural context drive the architectural response. Architecture design and Construction drawing design: Integrate external and internal structural solutions, daylighting and natural-ventilation strategies. BIM in planning and design, Solar energy: Link BIM to solar-path tools, simulate annual radiation, adjust window-to-wall ratios for optimum daylight and thermal control; high accuracy, high reliability [7]. Seasonal/daylight analysis: Import hourly/seasonal sky data to preview daylight performance for any moment of the year. Wind energy: Load local wind-rose (prevailing direction, speed, frequency) into the 3D model to set building orientation and identify the best micro-turbine layout. Ground-/water-source heat pumps: Combine soil-temperature and shallow-geothermal data to forecast long-term ground-temperature change, optimize pipe spacing and depth, and maximize renewable-energy yield. After the architectural design is completed, BIM can generate construction drawings design with a three-dimensional model. During this process, generating design drawings through data can save a lot of human, material and time costs. Example: Nanchang Construction-Waste Recycling Plant – Phase I. Tekla was used to optimize the steel structure (material choice, layout, section profiles). The process removed 166 interdisciplinary clashes, saved 90 calendar days and avoided 15 days of re-work [8]. It has reduced the labor and equipment costs associated with rework.

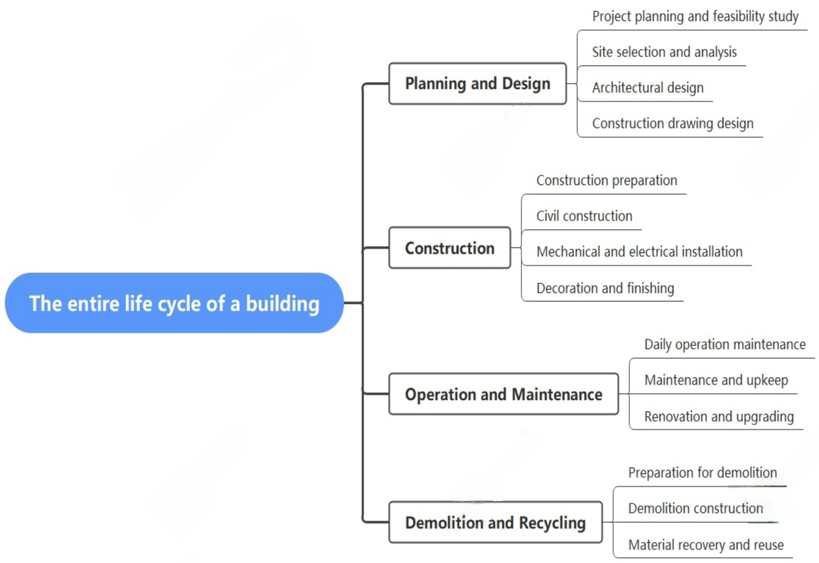

Figure 1. Four stages of the entire life cycle of a building.

2.2. Construction

As shown in **Figure 1** during the construction phase, for construction preparation, a project construction schedule serves as the primary implementation plan, outlining the overall timeline and progress management. This plan should comprehensively address material selection (prioritizing low-energy consumption and recyclable building materials), equipment configuration, technical approaches, and workforce allocation. Concurrently, real-time on-site monitoring enables progress tracking, risk assessment, and timely adjustments. The application of BIM technology in construction scheduling proves particularly valuable. When developing schedules, BIM provides extensive project-related data, allowing precise tracking of construction milestones, process timelines, and specific duration. The visualized final schedule clearly demonstrates inter-process dependencies, critical milestones, and time-frames, facilitating adjustments. For civil construction, engineering quantities can be calculated and costs can be estimated with nim technology. BIM can automatically generate engineering quantity lists, such as earthwork volume, concrete volume, and steel tonnage. It can achieve rapid and accurate cost estimation and dynamic cost control. Digital layout and construction guidance can be carried out: Import the BIM model coordinates directly into total stations, GPS measurement equipment or intelligent construction machinery to realize high-precision automated on-site layout and construction control, thereby improving efficiency and quality. Furthermore, BIM establishes specialized databases containing material properties, regional cost variations, equipment specifications, maintenance schedules, and technical evaluations. By integrating this data with building information modeling (BIM) to create 3D models, it simulates material combinations, structural configurations, and technical implementations. This enables accurate calculation of required resources including materials, equipment, technologies, and labor. By establishing an optimal combination that minimizes energy consumption, maximizes resource utilization, and reduces environmental impact, the project can simultaneously reduce material, equipment, and labor costs. During construction, BIM technology enables real-time regulatory monitoring, facilitates risk simulation assessments, identifies potential issues, and allows timely adjustments. For mechanical and electrical installation, BIM can detect whether there are physical conflicts between pipes and pipes, or between pipes and structures. It can also check whether the required operation space for installation, maintenance, insulation. Moreover, it can verify whether the design complies with the standards, and then divide the complex pipeline system into standard prefabricated components and modules. Processing drawings and data are directly exported from the BIM model and sent to the factory for automated production. For decoration and finishing, on the one hand, BIM can directly attach material textures to walls, ceilings, etc. in the model and adjust colors, joint sizes, and laying methods in real time, down to the millimeter level. This makes the selection of surface materials and design decisions more precise which diminishes the cost and the use of materials. On the other hand, before construction, BIM can automatically detect spatial conflicts between the decoration surface layer and concealed works. Example: New Jiangxi Integrated Chinese-Western Medicine Hospital (Yaohu Branch). BIM-based construction simulation detected design-to-site collisions, optimized tower-crane positions with visual-scripting, and delivered AR models to field crews for MEP installation. Result: 120 days shorter schedule, CNY 8 million direct cost saved (50 days and CNY 0.8 M for structure; 70 days and CNY 1.2 M for MEP) [8].

2.3. Operation and maintenance

As shown in **Figure 1**, for daily operation maintenance, during the operational phase, BIM technology is utilized to visually represent properties in three-dimensional models using color-coded states (e.g., for properties in transaction or rental status), enabling real-time status tracking. For transaction management, it provides intuitive price visualization for properties undergoing transactions. In rental management, it displays tenant details (name, contact information, move-in date, lease term), streamlines rental resource allocation, and reminds tenants to renew contracts promptly, reducing the cost of manual inspection. For maintenance and upkeep and renovation and upgrading, the billing management system handles utility charges for water, electricity, and natural gas. BIM also enables detailed energy consumption tracking and precision calculations to optimize resource usage. The maintenance phase involves structural inspections, upkeep of fire safety systems, elevators, and indoor environmental quality [9]. By integrating BIM with real-time building data, energy consumption is monitored in real-time, while maintenance teams track building performance metrics. This allows proactive equipment adjustments to avoid emergency energy waste. Through networked sensors, BIM analyzes data to identify resource wastage (water, electricity, lighting) and automatically triggers corrective measures, enabling real-time parameter adjustments via network-driven devices. Example: Shanghai No. 1 Intermediate People's Court. An integrated "BIM + system integration + O&M" platform fused big-data analytics, as shown in **Table 1**, cutting coal-equivalent energy use by 24.2 tce and saving CNY 0.596 5 million in 2016–2018 (energy-reduction rate > 10 %) [10].

Table 1. Energy consumption ratio of Shanghai no.1 intermediate people's court from 2016 to 2018

Year	Power consumption (kWh)	Gas consumption (m^3)	Water consumption (t)	Building coal energy consumption (tce)	Total cost (yuan)
2016	5800560	47080	60587	1731.75	5,707,500
2017	6086440	47261	65498	1814.32	5,777,200
2018	5729801	44143	65826	1707.56	5,104,000

Source: Evaluation Report on "Application of BIM Platform for Green Transformation" by the State Administration for Public Institutions.

During the pandemic, BIM technology was found to effectively control disinfectant usage and enable real-time ventilation, achieving optimal sterilization results. Furthermore, BIM technology facilitates public services by integrating information on nearby healthcare facilities, gas stations, and essential goods procurement points into the platform, enabling visualized queries and enhancing residents' convenience [10].

In addition, the pandemic revealed that BIM can ration disinfectant and trigger instant ventilation to achieve sterilization. At the same time the model becomes a citizen-service portal: healthcare facilities, gas stations and grocery pick-up points around the estate are plotted in 3D for quick, visual queries that make daily life easier.

2.4. Demolition and recycling

In Demolition and recycling， as shown in **Figure 1**, for preparation for demolition, a sound demolition plan must reflect structure type, site topography and material categories, then prescribe recovery routes and final destinations so that every component is re-used to the maximum. Data-rich dismantling: the pre-exist BIM keeps exact member sizes, joint details and material properties, allowing a reliable FEM model to be generated without expensive re-surveying; rebar, ducts and cables are visible in 3D so clashes and hazards are spotted before a wall is touched [11]. Method selection: the platform weighs manual, mechanical and implosive techniques against structural behavior and environmental impact, then evolves the optimum scheme. For demolition construction. During the building demolition process, the role of BIM is to ensure the implementation of the initial planning through digital management and dynamic visualization. It also handles unexpected situations on the site and achieves safe, orderly and resource-efficient demolition. On the demolition site, the BIM model guides each operation. Workers can check the BIM disassembly model of a certain area or floor on their computers at any time, which is more convenient than traditional two-dimensional drawings. Managers can use the BIM model for 4D progress tracking. Through drone aerial photography or on-site photography, real-time comparisons of the construction site can be made, quickly identifying delays in progress or deviations in the demolition scope. With BIM, construction personnel can dynamically mark dangerous areas and equipment operation ranges in the model, providing safety warnings for on-site personnel. For material recovery and use, Material inventory: because every element was classified (door, window, wall, column, beam, slab) and its material attribute logged at design stage, BIM can instantly quantify types and volumes with high accuracy [12]. Algorithms then match stock to local topography, what can be back-filled on site, what can be re-sold, what must be recycled, updating the model until the best logistics plan emerges. Example: oil-refinery unit demolition. BIM families were built for 20 + rigs, mobile cranes, scissor lifts, hydraulic breakers and clash-checked against the plant model 153 times. Detecting insufficient access routes and slewing-radius conflicts in advance eliminated stand-downs, shortened the demolition programmed by 10 % and saved USD 1.5 M [13].

3. Case study

3.1. BIM on Chongqing raffles city

3.1.1. Project overview

Chongqing Raffles City sits at the city's core, between Chaotianmen Plaza and the Jiefangbei CBD. The sail-shaped complex totals 1.12 million m^2; Lot B alone covers 630,000 m^2 on a 91,200 m^2 footprint. Four main towers are linked by a "crystal sky-bridge" whose free-form curtain wall was identified early as the most difficult element to design and install.

3.1.2. How BIM was used

(1) Design phase

Designers exploited BIM's 3D visualization to convert 2D drawings into a parametric Rhino model, allowing rapid optioneering for the sky-bridge geometry.

(2) Clash detection

Instead of sending surveyors to site, the Rhino curtain-wall model and the main-steel model were imported into a single BIM environment. Overlay checks revealed seven hard clashes between facade panels and primary structure, problems that would have been discovered only during erection under a traditional workflow.

(3) Construction simulation

All trades met in the unified BIM environment, rehearsed the erection sequence digitally and verified access, crane positions and temporary works before committing resources.

(4) Results

The digital rehearsals eliminated field surprises, cut rework and delivered a measurable saving in both cost and schedule while enabling millimeter-level, fine-tune construction of the complex curtain-wall system [14].

3.2. BIM on Jilin province modern seed industry park construction project

The "Jilin Province Modern Seed Industry Park Construction Project" that won the "Youlu Cup" National BIM Technology Competition. During the construction phase of this project, BIM technology was applied [15]. The project included an office building for enterprise research and an equipment building for the enterprise. For example, as mentioned earlier, BIM can solve problems such as physical conflicts and so on. This project used the BIM model to assist in the review of drawings, effectively identified and solved the "errors, omissions, deficiencies, and collisions" in the design, and further optimized the design scheme. Through BIM technology, the project achieved deepening of drawings, virtual roaming, process simulation and space analysis. Combined with prefabricated construction, the efficiency of equipment installation in the machine room was significantly improved [15]. Through in-depth exploration of this project, it also utilized the BIM management platform to enable multiple parties to communicate and solve drawing problems on the same platform. At the same time, the management platform was used for real-time monitoring and management during the construction process, and the building process of the project was dynamically tracked.

In summary, BIM technology, through digital modeling to establish three-dimensional models and by connecting various professionals through the platform, has significantly improved the efficiency of construction, reduced risks and errors during the construction process, and provided excellent technical measures for reducing energy consumption, minimizing environmental impact, and enhancing the comfort of residents' living. However, as BIM continues to develop, there are also more and more problems in aspects such as data leakage and usage scale limitations that urgently need to be improved.

4. Limitations of BIM technology

(1) BIM technology is not suitable for small-scale or short-term projects, but rather for large-scale projects with ample time. To address this, BIM can be applied to specific phases of smaller projects, allowing them to adopt BIM technology within budget constraints.

(2) In internet data transmission, there exists a risk of data leakage or tampering. To address this issue, block-chain technology can be utilized to mitigate such risks. As a core supporting technology for decentralized distributed storage and peer-to-peer trusted data networks, block-chain serves as the backbone of digital cryptocurrency systems represented by Bitcoin. By writing the hash values of critical nodes in BIM models into the block-chain, it ensures that any data tampering can be detected and traced.

(3) BIM software is tightly integrated with various internet management platforms. Since data analysis tools come from different vendors, there are differences in data formats and communication protocols. To address this, an intermediate converter can be developed to coordinate the conversion of various data formats and protocols.
(4) The maintenance of BIM technology involves costs, and its application in architectural design requires interdisciplinary professionals, which also incurs training expenses. To address this, two solutions emerge: First, in the digital age, educational platforms can be developed to deliver BIM training, consolidating resources to reduce offline teaching costs. For instance, courser offers BIM courses from global universities covering Revit modeling, BIM collaboration, and construction management, enabling systematic learning. Second, during recruitment, companies can set higher requirements for BIM-related positions, such as requiring certifications like BIM modeling engineer or national BIM application certifications, thereby reducing corporate training costs.

5. Conclusion

The application of BIM in construction spans the entire four stages of a construction project, creating a digital building model that incorporates all engineering data information. This change has improved the traditional construction mode and BIM also drives the construction industry towards a green, digital and intelligent transformation. However, during the development of technology, there are still some issues that need to be resolved. The future of BIM technology application remains arduous and long.

Disclosure statement

The author declares no conflict of interest.

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

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

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

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1. Introduction

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

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

2.1. Analysis of disaster mechanisms of different extreme weather events

2.1.1. Mechanism of rainstorm disasters

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

2.1.2. Mechanism of heavy snow disasters

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

2.1.3. Mechanism of low-temperature freeze-thaw disasters

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

2.1.4. Mechanism of strong wind and sandstorm disasters

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

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

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

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

2.3.1. Risk level classification

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

2.3.2. Construction of risk assessment model

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

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

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

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

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

3.1.1. Site avoidance technology under extreme weather zoning

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

3.1.2. Optimized design of route alignment and tunnel entrance location

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

3.2. Disaster-resistant protection technologies for tunnel entrances

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

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

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

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

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

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

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

3.3.1. Reinforced design for leakage resistance of the lining structure

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

3.3.2. Frost resistance design

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

3.3.3. Design for wind load and temperature stress resistance

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

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

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

3.4. Disaster-resistant design techniques for tunnel drainage systems

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

3.5. Disaster-resistant design techniques for ancillary facilities

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

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

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

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

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

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

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

4.1. Extreme weather monitoring and early warning technology

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

4.2. Disaster resistance maintenance and reinforcement technology during operation period

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

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

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

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

5.1. Emergency response technology system

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

5.2. Rapid post-disaster assessment and repair techniques

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

5.3. Post-disaster operational recovery and optimization adjustments

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

6. Conclusion

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

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

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

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

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

Disclosure statement

The authors declare no conflict of interest.

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Performance Analysis and Optimization Path of Connection Nodes in Prefabricated Building Structures

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Abstract: As one of the core technologies for force transmission and deformation coordination in prefabricated building structures, the performance of connection nodes directly determines the overall safety, stability, and durability of the structure. With the current changes in prefabricated building structures, the performance of traditional connection nodes has gradually exposed many problems. Based on this, this paper analyzes the performance and significance of connection nodes in prefabricated building structures and explores their optimization paths, aiming to provide theoretical support for the efficient construction and high-quality development of prefabricated buildings.

Keywords: Connection nodes; Performance; Prefabricated buildings; Industrialization; Construction

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1. Introduction

Guided by the development strategies of green buildings and new building industrialization, prefabricated buildings have become the core direction for promoting the transformation and upgrading of the construction industry due to their significant advantages such as energy conservation and emission reduction, efficient construction, and controllable quality. The overall performance of prefabricated building structures is highly dependent on the connection nodes between components. They can not only ensure the strength and stability of the connection parts, improve the safety of the entire prefabricated building structure but also optimize disaster resistance performance such as seismic and wind resistance. In extreme weather or natural disasters such as earthquakes, the building can maintain structural integrity and protect people's lives and property safety [1]. Against this background, systematically conducting research on the performance analysis and optimization of connection nodes, accurately revealing the force mechanism and failure law of nodes, and constructing a scientific and effective optimization system have become an urgent demand for industry development.

2. Performance analysis of connection nodes in prefabricated building structures

2.1. Mechanical performance

The force situation of connection nodes in prefabricated building structures is relatively complex. Connection nodes occupy an important position in the prefabricated building system, undertaking the important functions of connecting load-bearing parts, transmitting forces, and ensuring structural stability. From this perspective, the quality of mechanical performance directly affects the stability and safety of the entire prefabricated building system [2]. At the same time, since connection nodes play the role of connecting different components, to ensure the smooth transmission of forces between components, it is necessary to realize the reasonable distribution and conversion of various loads such as axial force, shear force, and bending moment between components through a reasonable force transmission path, and ensure the requirements of structural stability. Bearing capacity, as the main quantitative standard of the mechanical performance of connection nodes, mainly considers the influence of the node itself and various related parameters on the bearing capacity level during this process, focusing on the ultimate bearing capacity of the node and the bearing capacity under the serviceability limit state, so as to understand the critical failure state of the node under overload conditions and the total load it can bear. In addition, an ideal connection node should also have a certain elastic-plastic deformation capacity, which can not only meet the changes in displacement requirements during the structural work but also have a certain plastic deformation capacity to reduce energy, so that the structure will not suffer sudden damage under extreme loads.

2.2. Seismic performance

As the connection hub between components, connection nodes need to bear alternating stresses caused by cyclic loads, and their seismic performance directly determines the overall seismic resilience of the structure. On the one hand, energy dissipation capacity is the core indicator of the seismic performance of connection nodes, referring to the ability of the node to dissipate seismic energy through plastic deformation, frictional sliding, and other methods under cyclic loads. The stronger the energy dissipation capacity of the node, the more significant the seismic protection effect on the overall structure, which can effectively reduce the transmission of seismic energy to the main structure and reduce the risk of component damage [3]. On the other hand, ductility refers to the ability of the node to produce plastic deformation without losing bearing capacity. Good ductility can enable the node to produce large plastic deformation under earthquake action to dissipate energy, avoid sudden brittle failure, and provide a buffer space for structural seismic resistance.

2.3. Durability performance

Compared with the main structural components, connection nodes are more susceptible to erosion by external environmental factors due to their complex structure and numerous splicing interfaces and gaps, and their durability degradation rate is usually faster. Once the node is damaged due to insufficient durability, it will directly lead to a decline in the overall performance of the structure and even trigger safety accidents [4]. Therefore, it is necessary to consider the comprehensive effect of environmental factors and the node's own characteristics from the perspective of long-term service to understand the performance change mechanism. Due to the influence of external factors, the durability of nodes is easily affected by temperature and humidity changes, acid-base salt erosion, freeze-thaw cycles, and carbonation, leading to cracking of splicing interfaces, aging and failure of sealing materials, thereby damaging the watertightness and airtightness of nodes and creating conditions for the intrusion of other erosion factors.

In addition, it is necessary to focus on the impact of node structural details on durability. Structural details such as the splicing method of nodes, sealing treatment, and the quality of anti-corrosion coatings directly determine the erosion resistance of nodes. For example, insufficient selection and construction quality of sealing materials will lead to the failure of node gap sealing and exacerbate the intrusion of environmental media. According to the influencing factors of node durability, the degradation law and key influencing factors of nodes in long-term service environments can be clarified, providing a theoretical basis for the optimal design of node durability, the formulation of protective measures, and long-term maintenance, and ensuring the safety of prefabricated building structures during long-term service [5].

3. Significance of performance optimization of connection nodes in prefabricated building structures

3.1. Improve the safety of prefabricated building structures

As a modern building technology, the core of prefabricated buildings lies in decomposing the building structure into prefabricated components, which are standardized produced in factories and then transported to the construction site for rapid assembly, which extremely tests the safety of the prefabricated structure. Node performance optimization can accurately improve the mechanical performance and disaster resistance of nodes, ensuring that the building has sufficient bearing redundancy and deformation coordination capacity under static loads, earthquakes, strong winds, and other loads, effectively reducing the risk of stress concentration, avoiding premature node damage, and ensuring the overall stability of the structure under various load conditions [6]. At the same time, with the help of structural sealing design, improving material adaptability, and strengthening anti-corrosion and seismic measures, the intrusion path of environmental erosion media can be effectively blocked, the material degradation rate can be reduced, the service life of nodes can be prolonged, and thus the safety of the building throughout its life cycle can be guaranteed.

3.2. Promote green buildings and energy conservation and emission reduction

Compared with traditional cast-in-place buildings, prefabricated buildings have significant advantages in energy conservation and emission reduction during production, transportation, and assembly. Optimizing the performance of connection nodes can further optimize the production process of components, reduce material usage, and improve material utilization rate. Specifically, with the help of optimized structural design, the standardization and intensification of connection processes can be realized, the amount of on-site wet work can be reduced, and the dependence on large construction machinery can be reduced [7]. Optimized nodes often have better construction adaptability, which can improve component installation accuracy and connection efficiency, reduce rework and material waste during construction, and reduce carbon emissions during the construction phase. In addition, nodes have better durability and stability, which can reduce the sealing failure of the enclosure structure and the decline in thermal insulation performance caused by the degradation of node performance, avoid additional energy consumption and material waste caused by later maintenance and reinforcement, and ensure the energy-saving benefits of the building during long-term operation.

3.3. Promote the standardized and normalized development of the prefabricated building industry

With the improvement of standardization, the promotion and application of prefabricated buildings will be more extensive, which helps to form economies of scale and promote the transformation and upgrading of the entire construction industry. Research on node performance optimization can systematically sort out the performance influencing factors, force mechanism, and failure law of different types of nodes, establish a scientific node performance evaluation index system and design theory system, help clarify the design requirements, material selection standards, construction process parameters, and quality control points of nodes in different application scenarios, and fill the technical gaps in the industry in terms of refined node design and accurate performance evaluation, thereby forming a technical system covering the entire process of node design, construction, acceptance, and maintenance [8]. At the same time, optimizing node performance can promote the formation of standardized methods for node performance testing and evaluation, improve the scientificity and accuracy of node performance evaluation, and provide reliable technical means for engineering quality supervision.

4. Optimization path of connection nodes in prefabricated building structures

4.1. Select suitable building materials to improve the performance of connection nodes

Materials are the foundation for improving the performance of connection nodes in prefabricated buildings. Currently, to better ensure the stability of prefabricated building structures, it is necessary to solve the problems of single material selection, mismatched performance, and fast degradation rate of traditional nodes, focus on the performance complementarity and synergistic efficiency between multiple materials, and realize the overall improvement of node performance. In terms of material selection, it is necessary to reasonably select the concrete strength grade according to the force strength requirements and deformation needs of the node, balance strength and ductility, and avoid brittle failure of the node caused by high-strength concrete [9]. For example, the performance of concrete can be modified by adding fibers, mineral admixtures, etc., to improve its tensile strength, crack resistance, and wear resistance.

From the perspective of material performance, the performance parameters of different materials inside the node need to be accurately matched, such as concrete, steel bars, connectors, and sealing materials, to avoid interface failure or stress concentration caused by excessive differences in material performance. On the one hand, it is necessary to ensure that the thermal expansion coefficients of different materials are similar to reduce interface stress and cracks caused by temperature changes; on the other hand, it is necessary to realize the gradient transition of material stiffness and strength to avoid poor load transmission caused by sudden changes in material performance [10]. From the perspective of material environmental adaptability, it is necessary to select materials with targeted anti-degradation performance. In corrosive environments, corrosion-resistant materials such as corrosion-resistant concrete and stainless-steel connectors should be preferred, and high-performance anti-corrosion coatings and sealing materials should be used to build a multi-layer anti-corrosion system. In freeze-thaw environments, concrete materials with strong frost resistance should be selected, and the pore structure of concrete should be optimized to reduce the damage of freeze-thaw cycles to materials [11].

4.2. Improve construction quality control to ensure the practical effect of node performance

The improvement of the quality of connection nodes in prefabricated buildings is closely related to the safety and stability of the final structure, which involves three aspects: engineering technology, operators, and operating standards. First, the professional skills of construction personnel determine the quality of connection nodes. Therefore, when formulating skill training plans, it is necessary to combine the key links and special processes of node construction to improve the technical level and quality awareness of construction personnel. For high-precision connection, complex grouting and other links, it is necessary to ensure that construction personnel have certain qualifications and practical operation capabilities. In addition, special technical training should be organized regularly to make construction personnel familiar with the operation steps of grouting technology, prefabricated component positioning and hoisting, connector fastening, etc., to ensure the quality of node connection and the safety of the entire structure [12].

Second, the introduction of intelligent monitoring equipment provides technical support for connection quality control. It is necessary to calibrate and debug key equipment such as measuring instruments, grouting equipment, and fastening tools in advance to ensure that they achieve a precise and stable performance state, preventing and eliminating deviations in construction effects caused by improper equipment use; at the same time, it is necessary to establish an automatic early warning prompt function and an alarm feedback system to timely detect changes in grouting pressure, flow rate, and grout temperature, providing clear and clear data for operators to help them adjust construction parameters and operation processes in a timely manner [13]. In addition, it is necessary to introduce positioning instruments such as total stations and 3D scanners to conduct comprehensive inspections on important materials such as concrete, steel bars, connectors, and sealing materials, ensuring the quality of node construction from the material level; finally, establish a key process quality control point system. For core links affecting node performance such as component positioning, interface treatment, connection fastening, and grouting density, clarify quality control points, operation processes, and allowable deviation ranges to achieve precise control of the construction process.

4.3. Promote refined design of node structures to optimize the overall performance of nodes

As the basic carrier for the realization of node performance, structural design optimization needs to be based on the mechanical essence and service requirements of nodes, realizing the transformation from empirical design to precise design, and promoting the high alignment between node performance and the overall structural design goals. First, guided by the force characteristics of nodes, systematically analyze load types such as axial force, shear force, and bending moment, clarify the core path and auxiliary path of load transmission, and avoid the occurrence of force transmission blind areas or superposition phenomena [14]. At the same time, it is necessary to strengthen the redundant design of the force transmission path, build a backup force transmission mechanism outside the core force transmission path, improve the force transmission reliability of the node under extreme loads, and avoid the overall damage of the node caused by the failure of a single force transmission path.

Second, aiming at the problems of weak interface bonding, insufficient sealing performance, and poor seismic resilience of traditional nodes, it is necessary to refine structural details from multiple dimensions. For example, in terms of interface treatment, the roughness design of the connection surface of prefabricated components can be optimized, interface shear keys or concave-convex groove structures can be added to strengthen the bonding performance and anti-slip ability of the interface between new and old materials, thereby ensuring the coordinated force transmission of the interface [15]. Third, the refined design strategy of connection nodes in prefabricated buildings is reflected in multi-dimensional precise calculation and simulation analysis. A calculation model can be established to targetedly verify and detect the behavior of connection nodes under static loads, dynamic loads, and long-term loads, clarify the weak links of prefabricated building structures, and thus accurately adjust key design parameters, building material dosage, and the diameter and distribution form of steel bars to ensure the smoothness of the force transmission path and the stability of the structure.

5. Conclusion

In summary, with the continuous improvement of social requirements for building speed, quality, and environmental protection, prefabricated buildings are gradually becoming the mainstream of the construction market due to their fast, efficient, and environmentally friendly characteristics. By selecting suitable building materials, improving construction quality control, and promoting refined design of node structures, the performance and quality of prefabricated buildings can be improved, their competitiveness in the market can be enhanced, new competitive advantages can be brought to construction enterprises, the market demand for high-quality buildings can be met, and thus stand out in the fierce market competition.

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Study on Static Three-Component Aerodynamic Force Coefficients of a Streamlined Box Girder Based on CFD

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Abstract: A systematic investigation on the static three-component aerodynamic force coefficients of a streamlined box girder cross-section is conducted using the Computational Fluid Dynamics (CFD) approach. The Reynolds-Averaged Navier–Stokes (RANS) equations coupled with an appropriate turbulence model are employed to establish numerical simulation models of the bridge girder under various angles of attack. The flow field structures and aerodynamic characteristics around the main girder are simulated and analyzed in detail. By comparing the variations of lift, drag, and moment responses under different angles of attack, the characteristic curves of the three-component force coefficients are obtained. Furthermore, the locations of key flow separation points, the evolution of wake vortex structures, and their influences on aerodynamic force variations are examined to elucidate the underlying flow mechanisms governing the changes in aerodynamic coefficients. The results provide theoretical insights and technical support for wind-resistant design, aerodynamic optimization of streamlined box girders, and the selection of wind tunnel test parameters.

Keywords: Streamlined box girder; Computational fluid dynamics (CFD); Static aerodynamic force coefficients

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1. Introduction

In recent years, with the continuous increase in the span length of long-span bridges, bridge structures have become increasingly sensitive to wind loads, making aerodynamic characteristics a critical issue in structural design and safety assessment. Computational Fluid Dynamics (CFD) has emerged as an efficient numerical tool for predicting flow fields and aerodynamic force coefficients around bridge decks and has been widely applied in the study of bridge sectional aerodynamics.

Previous CFD studies have primarily focused on investigating the effects of different turbulence models on aerodynamic force coefficients and exploring the influence of geometric parameters on aerodynamic responses [1–5]. Zheng et al. proposed a CFD–Kriging surrogate-based shape optimization strategy to enhance the critical flutter wind speed and mitigate unfavorable aerodynamic effects, providing an effective approach for aerodynamic shape optimization [6]. Further studies analyzed the aerodynamic characteristics of twin-slot box girders under various flow conditions, demonstrating that geometric modifications can significantly alter static aerodynamic coefficient trends and flow separation behavior [7]. In addition, Li et al. conducted comparative CFD studies on the aerodynamic differences among trains, flat plates, and streamlined box girders, revealing the mechanical response characteristics of different structural forms from an aerodynamic perspective and offering valuable references for wind-induced response analysis of bridge-train systems [8].

These studies indicate that high-fidelity CFD simulations can effectively capture the sensitivity of aerodynamic force coefficients to angle of attack and geometric parameters, thereby providing a solid theoretical and numerical foundation for aerodynamic optimization of bridge structures.

In this study, a CFD-based numerical simulation method is employed to establish a comprehensive two-dimensional computational model incorporating the main girder and key ancillary components. By systematically varying the angle of attack, the drag, lift, and moment coefficients of a streamlined box girder and the corresponding flow field evolution are investigated. The objective is to provide reliable numerical evidence for wind-resistant bridge design, aerodynamic shape optimization, and the formulation of wind tunnel testing schemes.

2. Numerical model

The computational model adopts a 1:20 scaled section model, including the stiffening girder, crash barriers, and pedestrian railings, to evaluate the overall static three-component aerodynamic force coefficients. The static aerodynamic forces acting on the bridge girder section can be expressed in either the body-fixed coordinate system or the wind-axis coordinate system. The girder cross-section is shown in **Figure 1**. Mesh generation is performed using ICEM CFD, and the flow field is solved using ANSYS Fluent. The boundary conditions of the computational domain are defined as follows: a velocity inlet with a uniform incoming wind speed of 5 m/s; a pressure outlet with zero reference pressure; symmetry conditions applied to the upper and lower boundaries; and a no-slip wall condition imposed on the girder surface.

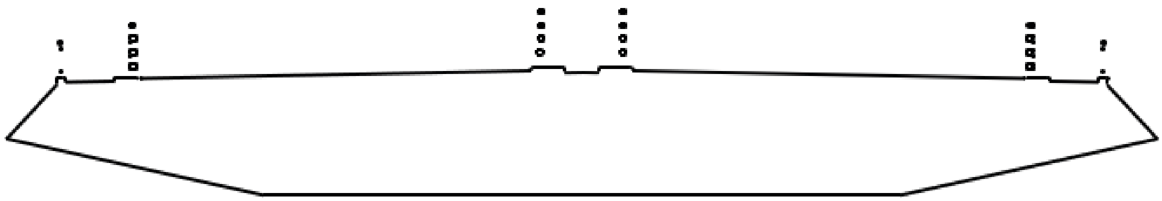

Figure 1. Schematic diagram of the main girder.

The SST k–ω turbulence model based on the Reynolds-averaged framework is employed. Second-order upwind schemes are used for spatial discretization, and the time step is set to 1×10^{3} s. A hybrid mesh is adopted, with the first near-wall grid height of 1.0×10^{-5} m, 20 boundary layer grids, and a growth rate of 1.1. The total number of grid cells is approximately 420,000. **Figure 2** presents the computational domain and mesh distribution under the 0° angle of attack condition.

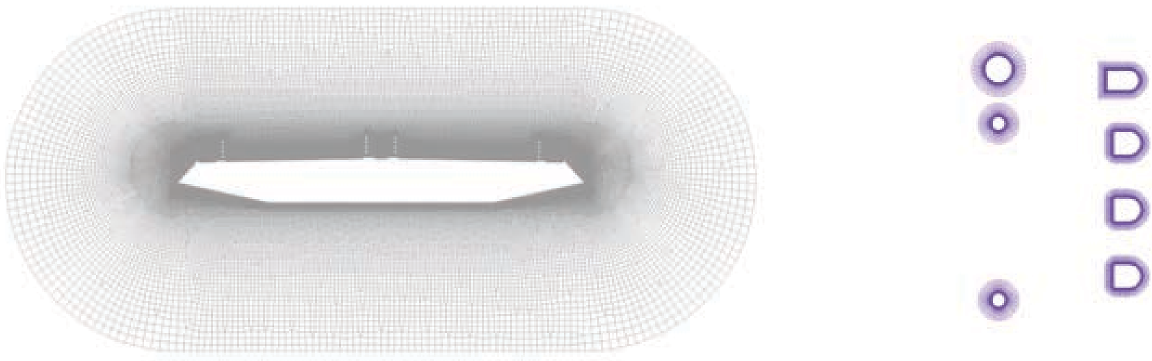

Figure 2. Overall computational domain and local mesh distribution.

3. Static three-component aerodynamic force coefficients

Figure 3 illustrates the variation of the three-component aerodynamic force coefficients in the body-fixed coordinate system as functions of the angle of attack. The results demonstrate that all aerodynamic coefficients are highly sensitive to changes in the angle of attack, reflecting the significant influence of inflow direction on flow structures and aerodynamic force distributions.

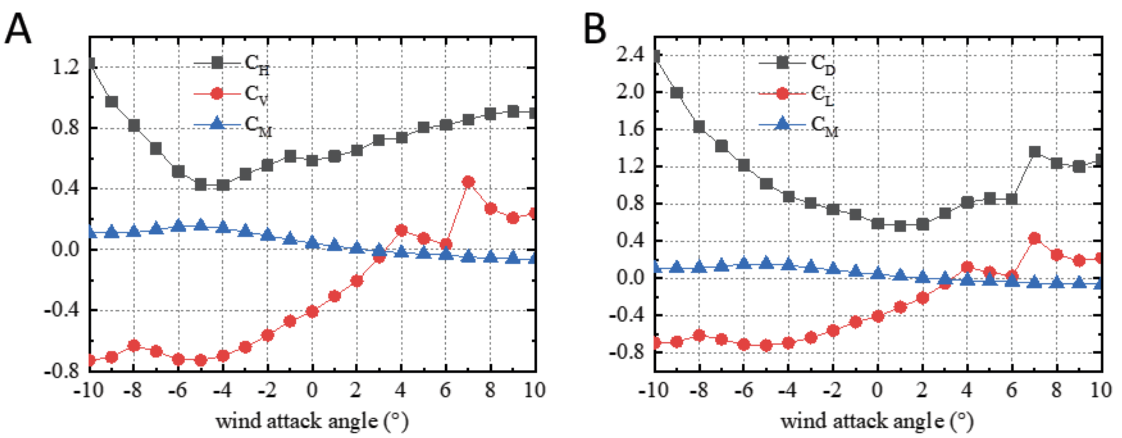

Figure 3. Static three component aerodynamic force coefficients. A. Body-fixed coordinate system. B. Wind axis coordinate system.

The drag coefficient exhibits a pronounced decreasing trend as the angle of attack increases from −10° to approximately −3°, reaching a minimum at a small negative angle of attack. This behavior indicates improved flow attachment along the girder surface and reduced wake size within this range, resulting in lower overall drag. As the angle of attack further increases, the effective windward projected area enlarges, accompanied by the development of local flow separation and recirculation zones, leading to a gradual increase in the drag coefficient, which remains relatively high at larger positive angles of attack. The lift coefficient shows an overall monotonically increasing trend with increasing angle of attack. It is negative in the negative angle range, gradually approaches zero, and becomes positive at positive angles of attack. This variation is closely associated with the redistribution of pressure on the upper and lower surfaces of the girder, indicating that changes in inflow direction significantly modify pressure gradients and dominant vortex structures. A local peak in the lift coefficient appears around angles of attack of 6–8°, which may be attributed to the intensification of separated vortex structures and changes in vortex shedding patterns. The moment coefficient maintains a relatively small magnitude across the entire range of angles of attack but exhibits a clear variation trend. At negative angles of attack, the moment coefficient is positive and decreases gradually with increasing angle, changing sign near zero angle of attack, indicating a reversal of the aerodynamic moment direction about the reference point. At positive angles of attack, the moment coefficient remains slightly negative, suggesting a certain degree of aerodynamic stability under these conditions. Overall, the numerical results reasonably capture the aerodynamic force variations of the streamlined box girder under different angles of attack, showing good consistency and continuity in the trends of the aerodynamic coefficients.

4. Flow field characteristics

Figure 5 presents the streamline distributions around the girder under different angles of attack. The results reveal that variations in the angle of attack significantly affect flow separation locations, wake morphology, and vortex structure evolution.

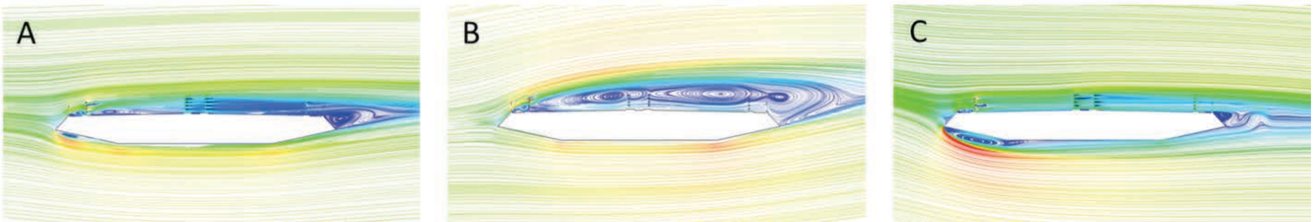

Figure 4. Surface streamline patterns of the main girder. A. 0° angle of attack. B. + 5° angle of attack. C. −5° angle of attack.

At 0° angle of attack, the incoming flow develops nearly along the girder axis, with relatively smooth streamline distributions on the windward side. The flow experiences slight acceleration near the leading edge and maintains good attachment along both the upper and lower surfaces. Although flow separation and recirculation occur in the wake region, the recirculation zone remains limited in size, and the wake is relatively narrow and symmetric, indicating a stable flow pattern with small aerodynamic force fluctuations.

When the angle of attack increases to + 5°, the flow field undergoes notable changes. The streamlines on the upper surface bend more sharply, and after local acceleration, flow separation occurs rapidly, forming a large recirculation zone and closed vortex structures above the girder. The separated vortices extend downstream and intensify in the wake region, significantly widening the wake. Meanwhile, the flow on the lower surface becomes more densely packed and remains more attached, resulting in pronounced asymmetry in surface flow characteristics and pressure distributions.

At −5° angle of attack, the flow separation behavior exhibits an opposite trend compared to the positive angle condition. The lower surface becomes the primary separation region, with noticeable flow deflection near the leading edge and the formation of a local recirculation zone. Although the size of the separated region is smaller than that observed at + 5°, it still significantly influences the wake structure. The upper surface flow remains largely attached, and the wake vortices develop predominantly along the lower surface, leading to an asymmetric wake displacement. A comparative analysis across different angles of attack indicates that variations in angle of attack substantially alter surface flow separation locations and wake vortex configurations, thereby changing the magnitude and direction of the aerodynamic forces acting on the girder.

5. Conclusion

Based on CFD numerical simulations, a systematic investigation is conducted on the static three-component aerodynamic force coefficients and corresponding flow mechanisms of a streamlined box girder under various angles of attack. The numerical results demonstrate that the static aerodynamic force coefficients are highly sensitive to changes in the angle of attack, with drag, lift, and moment coefficients exhibiting clear and continuous variation trends.

Changes in the angle of attack significantly affect flow separation locations on the girder surface and wake structure morphology, leading to modifications in pressure distributions and aerodynamic force responses. Analysis of streamline patterns and vortex structure evolution shows that the variations in aerodynamic force coefficients with angle of attack can be consistently and reasonably explained by the corresponding changes in flow field structures, indicating strong agreement between aerodynamic response characteristics and underlying flow mechanisms.

Disclosure statement

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Research Progress and Prospects on the Performance of Recycled Aggregate Concrete under High Temperature

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Abstract: This paper systematically reviews domestic and international research literature on the performance evolution of recycled aggregate concrete under high-temperature conditions in recent years. It summarizes the influence patterns of factors such as temperature, aggregate replacement rate, and fiber admixtures on the high-temperature performance of recycled aggregate concrete from the perspectives of macroscopic mechanical properties, microscopic degradation mechanisms, and performance improvement techniques. The analysis indicates that the interfacial transition zone is a weak link in the high-temperature damage of recycled aggregate concrete; its high-temperature resistance can be effectively enhanced through methods such as fiber reinforcement and alkali-activated cementitious systems.

Keywords: High-temperature exposure; Recycled aggregate; Performance

Online publication: Jan 28, 2026

1. Introduction

With the urgent need for global resource utilization of construction waste and sustainable development in the concrete industry, research and application of recycled aggregate concrete are becoming increasingly widespread [1]. However, compared to natural aggregate concrete, recycled aggregate exhibits high porosity, low strength, and high-water absorption due to the presence of adhered old cement mortar. These inherent defects raise significant concerns about the mechanical properties and durability of recycled aggregate concrete under complex conditions such as high temperatures and fires [2]. Investigating the performance degradation patterns and mechanisms of recycled aggregate concrete under high temperatures and developing effective reinforcement techniques are crucial for evaluating and enhancing the safety and fire resistance of recycled aggregate concrete structures. This paper aims to systematically review research achievements in this field in recent years, providing references for subsequent research and practice.

2. The influence pattern of high temperature on the macroscopic mechanical properties of recycled aggregate concrete

Macroscopic mechanical properties are central to evaluating the safety of concrete structures. Under high temperatures, parameters such as the compressive strength, tensile strength, and elastic modulus of recycled aggregate concrete exhibit significant deterioration characteristics with variations in temperature and aggregate replacement rate, and are regulated by heating and cooling regimes. The deterioration pattern differs from that of natural aggregate concrete [3].

2.1. High-temperature evolution characteristics of compressive strength

At low temperatures, water evaporation promotes densification of the cement paste, compensating for defects in the recycled aggregates. After reaching supercritical temperatures, strength decreases significantly, and the structure is completely destroyed under high temperatures. The higher the replacement rate of recycled aggregates, the more pronounced the deterioration. High replacement rates tend to form interfacial defects, accelerating strength loss and increasing brittleness. The higher the concrete strength grade, the relatively better the load-bearing capacity and stiffness after exposure to high temperatures [4].

2.2. Changes in tensile strength and bonding properties

Tensile strength is more sensitive to temperature, continuously decreasing with increasing temperature. The low-temperature enhancement effect is not significant, and the decrease in tensile strength at high temperatures is much greater than that of compressive strength. The core reasons are the initiation of micro-cracks in the interfacial transition zone and the weakening of the bond between new and old mortar. An increase in the replacement rate exacerbates deterioration [5].

Under high temperatures, the bonding properties between steel reinforcement and concrete also deteriorate, and the degree of deterioration decreases with increasing cover thickness [6,7].

The rise in temperature reduces the bond strength, and the rate of decline accelerates after high temperatures, which stems from the weakening of the matrix's gripping force and the thickening of the oxide film on the steel bars. The influence of the substitution rate is complex; at low substitution rates, the deterioration is close to that of natural aggregate concrete, while at high substitution rates, the deterioration is more pronounced, with the failure mode shifting from bond failure to splitting failure and increased brittleness [8,9].

Macroscopic mechanical properties are core indicators for assessing the load-bearing capacity and safety of concrete structures. Under high temperatures, the mechanical parameters of recycled aggregate concrete, such as compressive strength, tensile strength, and elastic modulus, exhibit significant evolutionary characteristics with increasing temperature and changes in aggregate substitution rates. These properties are also regulated by factors such as heating methods and cooling regimes, with their deterioration patterns differing from those of natural aggregate concrete [10].

2.3. Response of elastic modulus and deformation performance

The elastic modulus is a core parameter reflecting the stiffness of concrete. Under high temperatures, the elastic modulus of recycled aggregate concrete continuously decreases with increasing temperature, and the rate of decline is faster than that of compressive strength [11]. At room temperature, the elastic modulus of recycled aggregate concrete is already lower than that of natural aggregate concrete due to the high porosity of recycled aggregates and the weak interfacial transition zone, which makes internal microcracks more prone to develop under stress [12]. As the temperature rises, the hydration products of the cement paste decompose, pores increase, and microcracks expand, further reducing the elastic modulus until the material loses its stiffness.

The substitution rate of recycled aggregates has a significant impact on the elastic modulus, showing a monotonically decreasing trend with increasing substitution rates [13]. The type of fine aggregate can also affect the rate of deterioration. When both recycled coarse and fine aggregates are incorporated, the elastic modulus deteriorates faster than when only coarse or fine aggregate is incorporated separately [14]. In terms of deformation performance, the peak strain and Poisson's ratio at high temperatures exhibit a trend of "first decreasing and then increasing", with a distinct critical temperature: prior to the critical temperature, they decrease slightly with increasing temperature, which is related to the further hydration and densification of the cement paste; after the critical temperature, they increase significantly, with the rate of increase rising with temperature, due to the extensive expansion of internal micro-cracks and enhanced plastic deformation capacity. An increase in the replacement rate of recycled aggregate leads to a further increase in peak strain, with the peak point of the stress-strain curve shifting downward and to the right, and the curve becoming flatter, indicating a degradation in ductility and an increase in brittleness.

3. Microscopic deterioration mechanism of recycled aggregate concrete at high temperatures

The deterioration of the macroscopic mechanical properties of recycled aggregate concrete at high temperatures stems from internal microstructural damage and changes in chemical composition. The weak interface transition zone (ITZ) is the core reason why its high-temperature performance is inferior to that of natural aggregate concrete. Clarifying the deterioration mechanism is crucial for developing improvement technologies.

3.1. Characteristics of microstructural evolution

The microstructure of recycled aggregate concrete is complex, consisting of natural aggregates, old and new cement mortars, and multiple interface transition zones (ITZs), with the ITZs being the weak links [15]. At room temperature, there are two types of ITZs, both characterized by high porosity, loose structure, and numerous micro-cracks. The structural evolution at high temperatures exhibits temperature dependence: At low temperatures, only water evaporates, and the interface integrity is largely maintained. At medium temperatures, hydration products decompose, interface cracks initiate and propagate, bond strength weakens, and structural continuity is disrupted. At high temperatures, the interface completely detaches, forming a network of through-cracks, and the material integrity is lost. Studies have confirmed that after exposure to high temperatures, there is a significant increase in internal micro-cracks and pores, which propagate along the interfaces. The higher the replacement rate of recycled aggregates, the more pronounced the deterioration becomes [16].

3.2. Chemical and physical deterioration mechanisms

Microscopic deterioration is the result of the synergistic effects of chemical and physical degradation. Chemical deterioration manifests as the gradual decomposition of cement hydration products with increasing temperature, resulting in volume changes and internal stresses that accelerate the development of micro-cracks [17]. Physical deterioration encompasses three aspects: First, water evaporation generates vapor pressure, leading to cracks and spalling due to the obstruction of interface drainage. Second, differences in the thermal expansion coefficients of various components and internal-external temperature gradients generate thermal stresses, triggering interface cracks. Third, the mismatch in thermal expansion among the internal components of recycled aggregates produces additional stresses, exacerbating interface damage, which is a significant characteristic of its physical deterioration.

The deterioration of the macroscopic mechanical properties of recycled aggregate concrete at high temperatures stems from internal microstructural damage and changes in chemical composition. The weakness of the interfacial transition zone is the core reason why its high-temperature performance is inferior to that of natural aggregate concrete [18]. A thorough understanding of the microscopic deterioration mechanisms is of great significance for the development of targeted improvement technologies.

3.3. Application of microscopic characterization techniques

Microscopic characterization techniques serve as the core support for revealing the mechanism of high-temperature deterioration. Scanning electron microscopy (SEM) allows for the direct observation of internal pores, cracks, and interfacial states, and when combined with energy-dispersive spectroscopy (EDS), it enables the quantitative analysis of elemental composition [19]. X-ray diffraction (XRD) can clarify phase changes and verify the decomposition process of hydration products. Mercury intrusion porosimetry (MIP) quantitatively characterizes the deterioration of pore structure and reflects its correlation with macroscopic properties. Digital image correlation (DIC) provides real-time monitoring of strain and crack propagation, while nuclear magnetic resonance (NMR) precisely characterizes moisture states. The combined application of these techniques significantly enhances the depth of understanding regarding deterioration mechanisms.

4. Techniques for improving high-temperature performance of recycled aggregate concrete

In response to the high-temperature performance deficiencies of recycled aggregate concrete, various improvement techniques have been developed in academia, primarily focusing on fiber reinforcement and cementitious system optimization, among others. These techniques aim to compensate for the inherent defects of recycled aggregates from multiple dimensions and enhance their high-temperature resistance.

4.1. Fiber reinforcement techniques

This technique involves the incorporation of fibers to hinder the development of microcracks at high temperatures, improve ductility and crack resistance, and reduce spalling. Different types of fibers commonly used have varying focuses in their effects [20]. Steel fibers, which are highly resistant to high temperatures and possess high strength, achieve reinforcement across the entire temperature range by bridging cracks and enhancing interfacial bonding. However, their dosage must be controlled to avoid a decline in workability. Polypropylene fibers have low strength at room temperature and melt at high temperatures, forming pore channels that facilitate the escape of water vapor and reduce vapor pressure, primarily enhancing spalling resistance. They are often mixed with steel fibers to balance room-temperature performance and high-temperature spalling resistance. Inorganic fibers such as basalt fibers and carbon fibers can improve high-temperature performance; however, the former is costly, while the latter has the potential for health monitoring, making it a future research focus [21].

4.2. Optimization of the cementitious system

The cementitious system is the core factor influencing high-temperature performance, with optimization primarily achieved through the addition of mineral admixtures and the use of alkali-activated systems. Mineral admixtures (such as fly ash and slag) generate stable hydration products through secondary reactions, improving the microstructure [22]. Metakaolin exhibits significant high-temperature resistance but is costly, making it suitable for special environments. Alkali-activated cementitious systems are a novel green approach that utilizes alkaline activators to stimulate industrial waste slag, forming stable, high-strength hydration products. These systems demonstrate far superior high-temperature stability compared to traditional systems, maintaining good load-bearing capacity under high temperatures while reducing cement usage and carbon emissions, aligning with sustainable development goals and representing an important future direction.

4.3. Pretreatment methods for recycled aggregates

The inherent defects of recycled aggregates, such as high porosity and high-water absorption, are the root causes of their poor high-temperature performance. Pretreatment can enhance high-temperature resistance from the source, primarily through physical and chemical modification methods. Physical modification encompasses particle shaping, high-temperature calcination, and pre-wetting treatment: particle shaping removes aged mortar from the surface through mechanical means, optimizing the gradation and morphology; high-temperature calcination can close internal micro-cracks and densify the aged mortar, with enhanced effects when combined with particle shaping; pre-wetting treatment reduces the absorption of moisture from fresh paste by aggregates, improving interfacial bonding, but requires humidity control to avoid exacerbating damage from high-temperature steam pressure. Chemical modification strengthens interfacial bonding by applying reagents such as silane coupling agents and cement pastes, among which silane coupling agents can form a composite film to enhance high-temperature stability, significantly increasing the compressive strength retention rate at high temperatures and reducing interfacial cracks.

4.4. Optimization of mix proportion design

Rational mix proportion design can improve the internal structure and enhance high-temperature performance, primarily focusing on optimizing the water-binder ratio, adjusting aggregate gradation, and controlling the replacement rate of recycled aggregates [23]. The water-binder ratio must balance workability and high-temperature performance, as excessive ratios can increase porosity and reduce stability, necessitating experimental determination of the optimal value. Adjusting aggregate gradation using continuous gradation can enhance compactness, while incorporating lightweight aggregates such as vitrified microspheres can impede heat transfer, release steam pressure, and enhance fire resistance. The replacement rate of recycled aggregates is negatively correlated with high-temperature performance, with an optimal range existing where both room-temperature and high-temperature performances approach those of natural aggregate concrete; high replacement rates result in significant deterioration, requiring strict control in projects with high-temperature requirements, while general projects can appropriately increase the rate but require complementary reinforcement measures.

5. Conclusion

Recycled aggregate concrete, as the core technology for the resource utilization of construction waste, holds significant importance in promoting the sustainable development of the concrete industry. However, the issue of performance degradation under high-temperature environments restricts its large-scale engineering application. Although current research has made some progress, there are still many shortcomings. Future research can focus on the following areas: the law of performance degradation under the coupling effect of multiple factors, delving into the performance evolution under the coupling effect of temperature-load-erosive media to better align with actual engineering environments; performance restoration technologies after high-temperature exposure, developing efficient and cost-effective restoration materials and processes to extend the service life of structures; meso-macro coupled numerical simulation and prediction models to achieve accurate prediction of high-temperature performance; and the integration of engineering application technologies, formulating design codes and construction guidelines to promote large-scale application. With further research and technological innovation, the high-temperature resistance of recycled aggregate concrete will continue to improve, and its application scope will expand, providing strong support for the resource utilization of construction waste and the green and low-carbon development of the construction industry.

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Disclosure statement

The authors declare no conflict of interest.

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Research and Application of Comprehensive Protection Technology for High-Fill Embankment Slope: A Case Study of an Urban Road in Hunan Province

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Abstract: This paper takes the high-slope project of a newly built urban road in Hunan Province as the research object and systematically analyzes its geological conditions, hydrological characteristics, and slope stability issues. In response to the characteristics of high fill slope height (9–17.3 m) and high safety level (Level I), a comprehensive treatment plan was proposed, incorporating "anchored pile-sheet retaining walls, slope ratio method, interception and drainage, and greening protection". The paper elaborates on the design of the support structure, construction techniques, quality control, and deformation monitoring, with a particular focus on discussing the collaborative working mechanism between prestressed anchor cables and anti-slide piles, the timing control of layered filling and anchor cable tensioning, as well as the information-based construction and emergency response mechanisms. Research indicates that this plan demonstrates good applicability and safety under complex geological conditions and limited slope relaxation, providing a technical reference for similar high-slope projects.

Keywords: High slope; Anchor-pulled pile sheet retaining wall; Prestressed anchor cable; Deformation monitoring; Construction control; Geological disaster prevention and control

Online publication: Jan 28, 2026

1. Introduction

With the acceleration of urbanization in China, road construction is gradually extending to hilly and mountainous areas, leading to an increasing number of high slope projects [1–3]. Due to their complex geological conditions, poor stability, and high construction risks, high slopes have become a focal point and challenge in geotechnical engineering [4]. Hunan Province, characterized by its predominantly hilly terrain, abundant rainfall, and frequent geological disasters, makes the management of high slopes particularly crucial. This paper takes a high slope of a newly built urban road in Hunan Province as a case study to systematically analyze its engineering geological conditions, support structure design, construction techniques, and monitoring and control methods, aiming to provide references for similar projects.

2. Project overview

This project involves a newly constructed secondary arterial road in Hunan Province, with a total length of 912.899 meters and a designed speed of 30 km/h. A high fill slope exists in the section from K0 + 030 to K0 + 208.940, with a slope height ranging from 9 to 17.3 meters. It is a soil slope with a safety class of Class I and a designed service life of 50 years. The northwestern side of the slope is designated as urban planning land, with limited conditions for slope grading, necessitating the adoption of strong support measures.

3. Engineering geological and hydrogeological conditions

3.1. Climate and topography

This area has a subtropical humid climate with abundant precipitation, an average annual rainfall of 1,391.7 mm, and a maximum annual rainfall of 1,957.6 mm (recorded in 1977). The average annual evaporation is 1,281.7 mm. The annual average temperature is 16 ℃, with an extreme maximum temperature reaching 40.2 ℃ (on July 4, 1971). The annual average sunshine duration is 1,563.5 hours, and the freezing period occurs in January and February, with an average of 29 freezing days. The longest recorded frost and snow period spans 25 days, and the extreme minimum temperature is -7.5 ℃ (on January 30, 1977). The prevailing wind is from the northeast, with an average annual wind speed of 1.1 m/s and a maximum wind speed also reaching 1.1 m/s (in August and September). The average annual humidity is 81% [5].

The terrain along the project route generally slopes downward from higher elevations on both sides to a lower elevation in the middle, with significant topographical variations. The landform type in this area is characterized by dissolution-erosion hills, and microtopographically, it belongs to the middle slopes of these hills. The vegetation is sparse, with only a small number of shrubs and a few economic forests present. The ground elevation ranges from 310.68 to 330.45 m, with slopes ranging from 10–30°.

3.2. Stratigraphic lithology

The site consists of, from top to bottom, plain fill, red clay, strongly weathered dolomite, and moderately weathered dolomite. Among these, the red clay is prone to softening when exposed to water and is classified as a special soil type. The strongly weathered dolomite is considered extremely soft rock, while the moderately weathered dolomite is classified as relatively hard rock.

3.3. Hydrogeology

On the northwest side of the site lies a small stream with low and highly variable water flow, showing pronounced seasonal variations. The highest flood level in this river section is 295.00 m, which has no impact on the slope.

The catchment area of the slope engineering zone is approximately 15,000 m^2, with a drainage slope ranging from 10 to 30 degrees and a drainage length of about 130 m. The mountain slope has sparse vegetation. Surface catchment water causes severe erosion to the slope, so it is essential to implement effective slope interception and drainage measures to prevent erosion. The groundwater at the site primarily consists of bedrock fissure water. Due to the site's high elevation, the groundwater is deeply buried, and no groundwater was observed within the surveyed depth range during the investigation.

3.4. Seismic fortification intensity

According to the "Seismic Ground Motion Parameter Zonation Map of China" (GB18306-2015), the seismic fortification intensity in this area is 6 degrees, with the design earthquake group classified as Group I. The basic seismic acceleration for Class II sites is 0.05 g, and the characteristic period of the response spectrum for basic ground motion acceleration is 0.35 s. The site falls within a seismic fortification intensity zone of 6 degrees, with no liquefiable strata present. Therefore, the impact of liquefaction can be disregarded. Additionally, there is no weak soil, eliminating the need to consider seismic subsidence issues. The likelihood of landslides or collapses triggered by earthquakes is low, indicating good seismic stability of the rock and soil.

3.5. Unfavorable geology

The overburden of this line project consists of Quaternary soil layers, underlain by Cambrian dolomite with stable lithology and facies, indicating favorable engineering geological conditions.

4. Design of support structure

4.1. Design principles

A comprehensive support system integrating "anti-slide piles, retaining walls between piles, prestressed anchor cables, slope protection, and water interception and drainage" is adopted, taking into account stability, economy, and ecology.

4.2. Design of anti-slide piles

The piles have a diameter of 2 m, with a rectangular cross-section of 2 m × 2 m at the top. The pile length ranges from 13–27 m, with an embedded depth of ≥ 4 m into moderately weathered rock or an embedded length of ≥ 10 m. The pile shaft is constructed using C30 concrete, with a main reinforcement cover of 80 mm.

The retaining walls between piles are prefabricated components with a thickness of 0.4 m, width of 0.5 m, and length of 3.6 m, overlapping with adjacent anti-slide piles by 0.8 m on both sides.

4.3. Design of prestressed anchor cables

Each pile is equipped with 2 to 4 prestressed anchor cables, which consist of 12 strands of 15.2 high-strength, low-relaxation, double-layer PE-coated, unbonded prestressed steel strands with a standard tensile strength of 1860 MPa. The anchor hole diameter is 150 mm, and the inclination angle is 15°. The anchor cables are arranged at 2 m, 5 m, 8 m, and 11 m below the top elevation of the anti-slide piles, with the number of anchor cable channels determined based on the corresponding cantilever pile length.

4.4. Slope and drainage design

Above the pile top, a slope with a ratio of 1:1.5 and a height of 6 m is formed, protected by diamond-shaped grids and vegetation. Intercepting ditches and blind drainage ditches are provided, and the slope surface is covered with geogrids to enhance overall integrity.

4.5. Design of anchored pile sheet retaining wall

The larger value between the Coulomb earth pressure of the backfill behind the retaining wall and the landslide thrust is used for calculation. The values of calculation parameters for the backfill are as follows:

$$\gamma = 20\ \text{kN/m}^3,\ c = 10\text{kPa},\ \phi = 35°$$

5. Key construction techniques

5.1. Construction of anti-slide piles

5.1.1. Pre-construction preparation

Identify underground pipelines and develop relocation/protection plans; accurately set out and position, and construction can only commence after supervisor's review and approval.

5.1.2. Borehole formation and geological verification

The circular-square interface is located 2 m below the slope line; geological logging is required during drilling, and the pile length is dynamically adjusted: embedded in moderately weathered rock ≥ 4 m; if embedding is not possible, the pile length shall be ≥ 10 m.

5.1.3. Casing and pouring techniques

The steel casing is buried 2–4 m deep, with an inner diameter 20–40 cm larger than the pile diameter.

When the geological conditions are poor, mud wall protection + underwater pouring is adopted: the initial pouring depth of the tremie pipe shall be ≥ 500 mm; during pouring, the tremie pipe shall be buried 2–6 m deep; the pile top shall be over-poured by 0.5 m; and the sediment at the bottom of the hole shall be ≤ 50 mm.

5.1.4. Reinforcement and inspection

The reinforcement cage shall be protected against deformation, and guide pipes for anchor cables shall be pre-embedded; four acoustic detection pipes (compliant with JT/T 871-2013) shall be bound and extend 300 mm above the pile top.

5.1.5. Formwork and scaffolding

The formwork must be checked for strength, rigidity, and stability; a specialized plan must be prepared for scaffolding, with the verticality of upright poles being ≤ ± 75 mm.

5.2. Installation of retaining plate

5.2.1. Prefabrication and installation conditions

Prefabrication can be carried out in a factory or on-site, with lifting holes/drainage holes reserved; installation can only proceed after the strength of the anti-slide piles meets the standard.

5.2.2. Installation process

Excavate a trench between piles à compact crushed stones à place the retaining plate; the bottom of the plate should penetrate into the stable slope by ≥ 0.5 m; overlap with the pile by ≥ 800 mm, with the joint surface brushed with hot asphalt and lined with geotextile; pay attention to the installation direction to prevent breakage.

5.3. Filling of subgrade soil behind the wall

5.3.1. Base treatment

Clear vegetation, excavate steps on steep slopes (width > 2 m, inward slope > 4%); the degree of compaction of the foundation should be ≥ 85%.

5.3.2. Filling material and compaction

Prefer graded crushed stone soil with a particle size < 150 mm; a 0.5 m inverted filter layer (gravel/graded crushed stone) should be provided behind the retaining plate; fill in layers (each layer ≤ 30 cm), with a degree of compaction ≥ 94% (porosity of crushed stone soil ≤ 20%); large machinery was prohibited from rolling within 2 m behind the wall, and manual compaction should be used instead.

5.3.3. Drainage and reinforcement

Install blind drainage ditches (6 m long, inclined upwards at 10°, with a vertical spacing of 2 m); lay bidirectional geogrids (GSGS 80-80) at the interface between old and new soil: extend the laying to 4 m above the pile top, with a layer spacing of ≤ 1 m; ensure a longitudinal overlap width of ≥ 30 cm, which can be disconnected at anchor cable locations; secure with U-shaped nails (spacing 1.5 m × 1.5 m).

5.4. Anchor cable construction

5.4.1. Procedure

Drilling à Anchor Cable Fabrication à Hole Cleaning and Cable Insertion à Full-Hole Grouting à Tensioning and Locking à Anchor Sealing and Protection.

5.4.2. Drilling and anchor cable fabrication

Drill with casing, with a hole position deviation of ≤ ± 100 mm and an inclination deviation of ≤ 2%; the anchored section should penetrate into moderately weathered rock by ≥ 5 m; the anchor cable consists of unbonded steel strands (12 bundles of ϕ 15.2), with the PE sheath stripped and grease removed from the anchored section.

5.4.3. Grouting

Use cement paste (P • O 52.5, with a water-cement ratio of 0.42), with a strength of ≥ 40 MPa; ensure grout returns from the hole bottom, with a pressure of ≥ 0.5 MPa.

5.4.4. Tensioning and locking (Core process)

(1) Timing
When filling reaches 2m above the anchor cable elevation.

(2) Sequence
Perform cyclic and phased tensioning: first tensioning to 50% of the locking force; second tensioning to 100% of the locking force (after completion of upper layer filling).

(3) Control
Dual control of tensioning force and elongation value; work must be stopped for inspection if the error is within ± 5% to 10%.

(4) Safety
Supervised by designated personnel to prevent clip ejection, wire breakage, etc.

5.4.5. Anchor sealing and quality control

After tensioning, seal the holes and perform grouting; apply oil to exposed steel strands for corrosion protection. One set of test cubes (70.7 mm cubes) shall be reserved for every 30 anchor cables.

5.5. Backfilling construction of the platform in front of the piles

After the lowest row of anchor cables for piles A22# to A27# are locked, backfill and compact the area in front of piles A18# to A29# in layers. After completion, harden the area within 4 meters in front of the piles and set a 2% outward-sloping transverse slope.

5.6. Slope protection construction

The topmost retaining slab and the intercepting ditch at the top of the pile shall be cast in one piece, with drainage pipes embedded. Above the pile top, fill and compact according to the slope ratio à trim the slope à set out and excavate the foundation trench for the grid beam à pour concrete. After the grid beam reaches the required strength, backfill with 15 cm of planting soil, sow grass seeds, and plant shrubs.

6. Construction quality inspection

6.1. Pile body quality inspection

The quality of the pile body is fundamental to whether the anti-slide piles can perform their designed functions. In this project, non-destructive testing of all anti-slide piles is conducted using the sonic transmission method and the low-strain reflected wave method. The sonic transmission method can effectively identify the uniformity, continuity, and defect locations of the concrete in the pile body; the low-strain method is suitable for quickly evaluating the integrity and length of the pile body. For piles with detected abnormalities or those randomly selected based on a certain proportion, the core drilling method is employed for verification. Core drilling inspection allows for a direct assessment of the pile's concrete strength, the thickness of sediment at the pile bottom (with a control value ≤ 50 mm), and the lithology of the bearing stratum at the pile tip, making it the most direct means of evaluating pile quality. Additionally, a steel bar detector is used to re-inspect the position, spacing, quantity, and protective layer thickness of the steel reinforcement cage, ensuring that the steel reinforcement work meets design requirements.

6.2. Inspection of prestressed anchor cables

Prestressed anchor cables serve as crucial load-transferring components in anchored support systems, with their pullout resistance directly affecting overall stability. Prior to construction, basic tests are conducted in typical strata, with each group comprising no fewer than three cables, to verify the rationality of design parameters and construction techniques. During construction, anchor cables are randomly selected at a rate of 3–5% for acceptance tests to check whether their tensioning and locking values meet the design requirement of 1000 kN. Furthermore, the strength of the grouting mixture is tested through reserved specimens to ensure it is not less than 40 MPa.

6.3. Acceptance of concealed works

Concealed works, such as the installation of steel reinforcement cages, anchor cable drilling, blind drains behind walls, and the laying of geogrids, must undergo acceptance inspections before being covered. Only after passing the acceptance inspection can the next construction phase proceed, and complete visual and written records must be maintained to ensure quality traceability.

6.4. Basis for acceptance criteria

All construction quality acceptance shall strictly adhere to the "Technical Specification for Construction of Highway Subgrades" (JTG/T 3610-2019) and the "Quality Acceptance Standard for Construction of Building Slope Engineering" (GB/T 51351-2019) to ensure that both the project entity and its documentation comply with regulations simultaneously.

7. Deformation and settlement monitoring system

7.1. Monitoring content and methods

(1) Pile top displacement and settlement monitoring

Real-time monitoring of horizontal and vertical displacements at the pile top shall be conducted using precision leveling instruments or total stations (with accuracy ≤ ± 0.5 mm).

(2) Soil layer horizontal displacement monitoring

By embedding inclinometers, monitor displacements at different depths within the backfill behind the wall to identify potential slip surfaces.

(3) Anchor cable tension monitoring

Install steel string pressure sensors on no less than 10% of the total anchor cables, with a focus on monitoring the upper anchor cables that bear greater loads.

(4) Crack observation in backfill behind the wall

Conduct manual inspections to record the emergence, development, and closure of cracks.

7.2. Monitoring frequency and control standards

The monitoring frequency shall be dynamically adjusted according to the construction phase, as detailed in **Table 1**.

Table 1. Monitoring frequency and control standards

Monitoring item	Monitoring frequency	Control standard
Pile top horizontal and vertical displacement	At least once daily during subgrade filling; every 3–7 days after filling completion	Displacement ≤ 30 mm; Horizontal displacement rate ≤ 2 mm/day
Soil layered horizontal displacement	Every 3–7 days after filling reaches the pile top	—
Anchor cable tension	At least once daily during filling; every 3–7 days after filling completion; once monthly during operation period (monitoring duration ≥ 2 years)	≤ 1500 kN
Cracks in backfill soil	At least twice daily during filling; once every two days after filling completion	No cracks

Note: When the measured values change dramatically, the monitoring frequency should be increased. In emergency situations, it is imperative to immediately report to the construction, design, and supervision parties and take corresponding measures to address the issue.

7.3. Early warning and feedback mechanism

(1) When the measured value is less than 0.7 times the monitoring value, it is in a safe state;

(2) When the measured value reaches 0.7 to 0.9 times the monitoring value, it is in a critical state;

(3) When the measured value exceeds 0.9 times the monitoring value, it is in a dangerous state.

During the monitoring process, if the situation is safe, monitoring should continue according to the original plan, and a monitoring report should be provided before the next monitoring. If the situation reaches a critical or dangerous state, or if the measured horizontal displacement rate of the pile top exceeds 2 mm/d for three consecutive days, the monitoring frequency should be increased, and an alarm should be raised promptly. Monitoring results should be submitted on the same day, and a written engineering contact letter should be issued to notify Party A, the design, supervision, and construction parties.

8. Major construction hazards

The construction of high slopes is a high-risk operation prone to safety accidents due to the complexity of terrain and geological and hydrological conditions, as well as the relatively low quality of personnel involved. Through a comprehensive analysis of factors such as personnel, machinery, materials, methods, and environment, the following four hazards that may cause personal injury or property damage have been identified and confirmed:

(1) Mechanical injury

During mechanical operation, accidental mechanical failures or violations of operating procedures may result in personal injury or mechanical damage.

(2) Hole collapse injury

During the construction of anti-slide piles, from the excavation of pile holes to before sealing them, the failure to properly protect or waterproof the hole openings can easily lead to pile hole collapse, resulting in personal injury.

(3) Electric shock injury

If the outer edge of the project does not maintain a safe distance from external high-voltage power lines, electrical equipment lacks neutral or ground protection, protective equipment fails, high voltage is used for mobile or lighting purposes, or electrical equipment is used and operated in violation of regulations, personal injury or damage may occur.

(4) Formwork and scaffolding collapse injury

The construction of the cantilever section of anti-slide piles involves scaffolding and formwork engineering. If safety precautions are not taken during the construction process, the collapse of formwork and scaffolding can easily cause personal or mechanical injury or damage.

(5) Collapse and landslides

Improper construction methods, improper use of machinery, or construction during thunderstorm seasons during roadbed filling can easily lead to slope collapse and landslides, causing personal or mechanical injury or damage.

(6) Pipeline damage

Failure to ascertain pipeline locations before construction and causing pipeline damage during construction can easily deteriorate the construction environment and may also result in property damage and personal injury.

During the construction process, it is necessary to strengthen the prevention of the aforementioned major hazards to ensure construction safety.

9. Emergency measures

Slope support shall adhere to information-based construction, with corresponding treatment measures taken based on on-site conditions. Strengthen deformation monitoring, arrange dedicated personnel for 24-hour duty to observe deformation around the slope, promptly report any abnormalities, and initiate emergency measures.

9.1. Abnormal deformation at the pile top

Due to the complex construction process of the tension-anchor pile-sheet retaining wall structure, if abnormal deformation occurs in the pile during the filling and anchor cable tensioning processes, construction should be immediately halted, the cause should be investigated, remedial measures should be taken, and relevant parties such as the supervision and design units should be promptly notified to develop countermeasures.

9.2. Abnormal deformation at the slope crest

Given the complex geological conditions of the slope, if there are signs of slope instability during construction or phenomena such as cracks and abnormal settlement occur in the surrounding roads and flood interception ditches, construction should be immediately stopped. Timely measures should be taken to prevent rainwater scouring and infiltration, and relevant parties such as the supervision and design units should be promptly notified to develop countermeasures.

9.3. Severe rainwater scouring on the slope surface

Due to inadequate and untimely slope protection, rainwater severely scours the slope surface. Before the onset of heavy rain, the entire slope surface should be promptly covered with impermeable materials such as plastic sheeting, and the slope crest should be compacted with soil to prevent rainwater infiltration.

10. Conclusions and recommendations

For high-fill slopes under complex geological conditions, the comprehensive support system of an anchored pile-sheet retaining wall is technically feasible and safe and reliable. The key to construction lies in controlling the timing of layered filling and anchor cable tensioning, which effectively coordinates deformation. An information-based monitoring and early warning system is an important means of achieving dynamic design and risk management and control. Long-term maintenance and management are essential for ensuring the sustained stability of the slope.

Disclosure statement

The authors declare no conflict of interest.

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Design and Application of Intelligent Monitoring System for Bridge Construction Based on BIM + Internet of Things

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Abstract: To address issues such as data fragmentation, low visualization, and delayed early warning in traditional bridge construction monitoring, an intelligent monitoring system for bridge construction that integrates BIM (Building Information Modeling) and IoT (Internet of Things) technologies is proposed. Firstly, the core application requirements and technical challenges of BIM and IoT technologies in the field of bridge engineering are outlined. Secondly, a four-tier architecture system consisting of the "perception layer–transmission layer–data layer–application layer" was constructed, with a focus on explaining the functional modules, hardware selection, and software integration solutions at each level to achieve real-time collection, dynamic modeling, and intelligent analysis of key parameters such as structural stress, settlement, temperature, and equipment operational status during the construction process. Finally, based on an actual bridge engineering project, system application verification is conducted. By comparing the application effects of traditional monitoring methods with those of the intelligent monitoring system, the feasibility and superiority of the system in enhancing construction monitoring accuracy, efficiency, and safety management capabilities are validated.

Keywords: BIM technology; Internet of things; Bridge construction; Intelligent monitoring; System design; Engineering application

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1. Introduction

With the rapid development of China's transportation infrastructure construction towards large spans, complexity, and intelligence, the difficulty of bridge engineering construction has been increasing year by year, posing higher requirements for safety control and quality supervision during the construction process.

BIM technology, centered on three-dimensional digital models, enables information integration and visual management throughout the entire project lifecycle, providing an accurate information carrier for construction monitoring.

Meanwhile, IoT technology constructs a "connected everything" sensing system through various sensing devices, communication networks, and data processing terminals, enabling real-time collection and remote transmission of key parameters. The deep integration of these two technologies can break down the technological barriers of traditional monitoring models and achieve the goals of "real-time data, visualized models, intelligent analysis, and proactive control" during bridge construction [1]. Based on this, this paper designs an intelligent monitoring system for bridge construction based on BIM and IoT technologies. Through architectural optimization, software and hardware integration, and engineering application verification, it provides technical support for safety control in bridge construction and promotes the intelligent transformation of bridge engineering construction.

2. Integration mechanism and requirements of BIM and IoT technologies

2.1. Core logic of integration

The integration of BIM and IoT technologies aims to establish real-time mapping and closed-loop management between "physical construction" and "digital models". IoT is responsible for real-time collection of multidimensional physical data from the construction site, including structures, environment, and equipment, driving the evolution of BIM models from static design to dynamic construction twins. The BIM model serves as the hub for data integration and decision-making, enabling visual display, correlation analysis, and simulation forecasting of multi-source information. It then feeds back optimization instructions to the site, forming an intelligent closed loop of "perception-analysis-decision-control".

2.2. Key integration technologies

Deep integration relies on three categories of key technologies:

(1) Multi-source data integration technology

Based on standards such as IFC and XML, it unifies data formats and coding, and develops dedicated interfaces to achieve lossless interaction between IoT data and BIM platforms (such as Revit and Bentley) [2].

(2) Dynamic model updating technology

Based on real-time collected data, it employs algorithms to achieve automated and precise synchronization updates of the BIM model [3].

(3) Cloud-edge collaborative computing technology

It adopts an "edge computing + cloud computing" architecture. The edge side is responsible for real-time preprocessing and rapid warning, ensuring timely response; the cloud side is responsible for massive data storage, in-depth analysis, and global optimization, supporting scientific decision-making [4].

2.3. Core requirements for bridge construction monitoring

Bridge construction monitoring must meet the following core performance indicators: structural stress monitoring error ≤ ± 5%, settlement monitoring accuracy ≤ ± 0.1 mm; data acquisition cycle ≤ 10 s, transmission delay ≤ 5 s, warning response time ≤ 3 s; achieve real-time linkage and multi-dimensional interactive display of monitoring data with the BIM model; the system must adapt to high-temperature, high-humidity, and strongly interfering environments, with a hardware monthly failure rate < 0.5% and software failure-free operation time ≥ 720 h/month [5,6].

3. Design of an intelligent monitoring system for bridge construction based on BIM + internet of things

3.1. System design principles and core objectives

3.1.1. Design principles

(1) Practicality

Align with actual engineering needs, select easily deployable and operable hardware and software, and avoid technological redundancy;

(2) Scalability

Adopt a modular design, reserve standard interfaces, and support flexible expansion of functions and scenarios;

(3) Security

Implement full-process data encryption, strict access control, and network protection to ensure system and data security;

(4) Collaborative

Ensure compatibility and interoperability with existing management platforms and BIM design models to achieve business collaboration.

3.1.2. Core objectives

The system aims to achieve five major objectives: integrating multi-dimensional real-time data to build a unified monitoring data center and eliminate information silos; enabling visualization and dynamic correlation analysis of monitoring data based on BIM; establishing an intelligent hierarchical early warning system for early identification, early warning, and rapid response to risks; providing decision support for construction optimization through data mining and simulation to enhance safety and efficiency; and creating a comprehensive digital construction file to provide a data foundation for the entire lifecycle operation and maintenance of the bridge [7].

3.2. Overall system architecture design

Based on the four-tier architecture concept of "perception-transmission-data-application", the overall architecture of the intelligent monitoring system for bridge construction based on BIM + Internet of Things is designed. Each tier operates collaboratively from top to bottom, forming a complete monitoring loop, as shown in **Figure 1**.

Figure 1. Overall system architecture design.

The perception layer, serving as the data acquisition terminal of the system, is responsible for real-time capture of various key parameters and forms the foundation for system operation. The transport layer undertakes the task of data transmission, enabling interconnection and interoperability between the perception layer and the data layer. The data layer is responsible for data storage, processing, and standardization, providing data support for the application layer. The application layer, based on the BIM model, implements core functions such as data visualization, intelligent analysis, and early warning control, directly serving construction management decision-making. Each layer operates independently while collaborating synergistically to ensure the stability and efficiency of the system.

3.3. Detailed design of each layer

3.3.1. Design of the perception layer

The perception layer is responsible for multi-dimensional data acquisition of construction status. It is divided into three major modules: structural perception, environmental perception, and equipment perception, based on the monitoring objects.

Equipment selection adheres to the principles of accuracy, durability, and environmental adaptability, with deployment focusing on key load-bearing areas and risk zones [8]. The specific design is shown in **Table 1** below:

Table 1. Design of the perception layer

Perception module	Monitoring parameter	Selected equipment	Technical specifications	Deployment location
Structural perception module	Main Girder Stress	FBG Strain Sensor	Range: -200 to 1500 με; Accuracy: ± 1 με; Temp. Range: -40 to 85 °C	Mid-span, supports, and concentrated load areas of main girder
	Pier/Pylon strain	Resistance strain gauge	Sensitivity: 2.0 ± 1%; Measurement Range: -3000 to 3000 με; Protection: IP67	Lower-middle and top connection areas of piers/pylons
	Structural settlement	Hydrostatic leveling system	Accuracy: ± 0.1 mm; Range: 0–500 mm; Output: RS485	Pier/pylon foundations, key sections of main girder
	Horizontal displacement	Laser displacement sensor	Range: 0–50 m; Accuracy: ± 0.05% FS; Response Time: ≤ 1 ms	Top of piers/pylons on both sides of the bridge
Environmental perception module	Temperature	Digital temperature sensor	Range: -40 to 125 °C; Accuracy: ± 0.5 °C; Supply: 3.3–5V	Main girder, piers/pylons, and construction site periphery
	Humidity	Integrated temp./humidity sensor	Humidity Range: 0–100% RH; Accuracy: ± 3% RH; Output: Analog	Temporary site facilities, component storage areas
	Wind speed	Ultrasonic anemometer	Range: 0–60 m/s; Accuracy: ± 0.1 m/s; Strong anti-interference	Top of main girder, top of bridge erection machine
	Rainfall	Tipping bucket rain gauge	Range: 0–4 mm/min; Resolution: 0.1 mm; Output: pulse	Open area of the construction site
Equipment perception module	Equipment load	Pressure sensor	Range: 0–500 t; Accuracy: ± 0.2% FS; Protection: IP68	Crane hook, load-bearing parts of erection machine
	Operating speed	Hall effect RPM sensor	Range: 0–10,000 rpm; Accuracy: ± 1 rpm; Fast response	Output shaft of equipment motor
	Positioning precision	GPS positioning module	Positioning accuracy: ± 2 cm; Update rate: 10 Hz; BeiDou/GPS dual-mode	Mobile equipment (e.g., bridge erection machine, tower crane)

The deployment strategy for the perception layer combines focused coverage with redundant configuration. Sensors are densely placed at critical sections of bridges, vulnerable areas, and core components of large equipment to ensure the continuity and reliability of data acquisition.

3.3.2. Design of the transport layer

The transport layer is responsible for ensuring the stable and real-time uploading of data. Given the expansive scope and complex environment of construction sites, a hybrid transmission architecture combining "wired backbone network + wireless coverage network" was adopted.

(1) Wireless transmission

It utilizes the synergy of 4G/5G and LoRa technologies. 4G/5G is employed for transmitting large-bandwidth, low-latency services such as video and high-frequency sampled data, while LoRa is used to connect widely distributed, low-power sensors for temperature and humidity, with its long-range and high-penetration capabilities compensating for network blind spots.

(2) Wired transmission

Optical fiber and industrial Ethernet are used between the control center and fixed equipment to form a highly reliable, high-bandwidth data backbone. Additionally, by deploying relay nodes in areas with weak signals, encrypting data transmission with SSL/TLS protocols, and implementing data retransmission mechanisms, the coverage, security, and integrity of the transmission links are comprehensively ensured [9].

3.3.3. Data layer design

The data layer serves as the data hub of the system, adopting a "cloud-edge" collaborative storage and computing architecture to achieve full lifecycle management of data.

(1) Data storage

An industrial real-time database is deployed on the edge side to cache and process high-frequency real-time data, meeting local rapid response requirements. The cloud employs distributed databases and object storage to archive massive historical data, BIM models, and documentation, supporting elastic expansion and long-term preservation. An automated off-site backup mechanism was established to ensure data security.

(2) Data processing

A two-tier pipeline of "edge preprocessing + cloud-based in-depth analysis" is implemented. Edge nodes perform data cleaning, filtering, and compression, while the cloud conducts data fusion, calibration, and utilizes big data algorithms to mine data correlations and trends [10].

(3) Data standardization

Establish unified data coding, formatting, and exchange standards (e.g., adopting the IFC standard to unify BIM data) to break down information silos. Meanwhile, establish a data quality assessment and feedback mechanism to ensure the accuracy and usability of data flowing into the application layer.

3.3.4. Application layer design

The application layer serves as the interface for human-computer interaction. Based on a unified data foundation and BIM models, the following five core functional modules are developed:

(1) BIM visual monitoring

Dynamically associate real-time monitoring data with BIM models to enable visual representation of working conditions, data querying, and risk visualization. Support 3D navigation, component querying, and historical data retrieval, with automatic model alerts when data exceeds limits.

(2) Intelligent analysis and prediction

Integrate monitoring data with BIM simulation models to assess structural safety status, simulate and optimize construction plans, and predict equipment failures, achieving a shift from "post-event awareness" to "pre-event prediction".

(3) Hierarchical early warning and control

Establish a "blue, yellow, red" three-tier early warning system that automatically triggers multi-channel (audible and visual, SMS, platform) alarms based on thresholds and generates closed-loop handling work orders to track risk resolution.

(4) Construction progress management

Dynamically compare actual progress with BIM planned progress to visually present progress deviations, assisting in resource scheduling and plan adjustments.

(5) Digital archive management

Automatically archive data, reports, and documents throughout the entire construction process to form traceable and searchable digital twin archives, laying the foundation for delivery and operation and maintenance handover.

3.4. System hardware and software integration plan

3.4.1. Hardware integration

Hardware integration is carried out around the "sensing-transmission-processing" chain. The sensing layer aggregates data from various sensors through multifunctional data acquisition terminals; the transmission layer constructs a "wired + wireless" hybrid network using wireless gateways, optical fibers, and other equipment; the processing layer relies on edge and cloud servers for data storage and computation; users access the system through various terminals. During integration, emphasis is placed on equipment standardization and interface compatibility, and through reasonable physical deployment and protective design, stable operation of the hardware in complex construction environments is ensured.

3.4.2. Software integration

The software integration adopts an architecture of "BIM platform + IoT platform + application modules". The BIM platform is responsible for model construction and visualization, the IoT platform handles device connectivity and data scheduling, and the application modules, developed based on Python/Java, implement core business functions. By developing standardized data interfaces, efficient data interoperability among various platforms and modules is achieved. Additionally, the human-computer interaction interface has been optimized to enhance the system's usability.

3.5. System security and reliability design

3.5.1. Security design

System security covers three aspects: data, equipment, and permissions. This includes full-chain encryption and authentication for real-time data collection, transmission, and storage; physical protection and status monitoring of critical hardware equipment; and role-based hierarchical permission management for users, combined with dual authentication to ensure secure access.

3.5.2. Reliability design

Through hardware redundancy (hot standby for critical equipment, redundant sensor deployment), software fault tolerance (exceptional data handling, algorithm optimization, and regular maintenance), and rigorous industrial-grade environmental adaptability selection, the system ensures continuous and stable operation under complex working conditions.

4. System application validation and effect analysis

4.1. Project overview

To validate the system's effectiveness, a continuous beam bridge project with a main span of 180 meters across a river was selected as the application scenario. This project is characterized by its large span, complex environment (high humidity and strong winds near the river), and numerous large-scale equipment, posing significant challenges for traditional monitoring methods and providing a typical scenario for validating the system.

4.2. System deployment and commissioning

The deployment adhered to the design architecture, completing the installation of sensing equipment, network construction, central and terminal deployment, and software integration. During the commissioning phase, continuous testing and parameter tuning were conducted for 72 hours to evaluate hardware accuracy, network performance, software functionality, and system interoperability, ensuring that all indicators met standards and the system achieved a stable operating state.

4.3. Application process and data collection

The system operates continuously throughout the entire construction cycle. Taking the cantilever casting stage as an example, the system monitors the stress and deformation of the main beam, as well as the status of the bridge-erecting machine in real time. When the monitored data approaches the threshold, the system promptly issues warnings, guiding construction adjustments and successfully controlling risks at their inception. Throughout the project, over ten million data points have been collected, and the system has operated stably and reliably.

4.4. Analysis of application effects

Compared with traditional methods, the system has achieved significant improvements in core indicators, as shown in **Table 2**.

Table 2. Analysis of application effects

Evaluation dimension	Traditional method	Intelligent monitoring system	Improvement
Monitoring accuracy	Stress: ± 3.5%; Settlement: ± 0.3 mm	Stress: ± 1.8%; Settlement: ± 0.08 mm	Accuracy improved by 48–73%
Data acquisition efficiency	Manual, intermittent sampling	Automatic, continuous sampling (every 10 s)	Efficiency increased by orders of magnitude; manual labor reduced by 75%
Early warning timeliness	> 30 minutes (requires manual intervention)	≤ 3 seconds (automatic response)	Real-time response capability achieved
Hazard detection rate	65% (mainly overt hazards)	98% (including latent hazards)	Detection capability enhanced by 50%
Schedule control	Deviation rate: ± 5%	Deviation rate: ± 1.2%	Control precision significantly improved

The analysis indicates that the system has achieved precise monitoring, digital management, and intelligent decision-making, effectively ensuring construction safety, quality, and progress.

5. Conclusion

The intelligent monitoring system architecture integrating BIM and IoT proposed in this paper effectively addresses the fragmentation and lag issues of traditional monitoring, providing a comprehensive solution for real-time visualization and intelligent control of bridge construction. Through the collaborative design and engineering integration of the four layers of "sensing, transmission, storage, and application", the system achieves unified management and application of multi-source data, with its security, reliability, and scalability verified. Engineering practice demonstrates that the system can significantly enhance monitoring efficiency and safety management levels, holding significant value for widespread application. Future research can further optimize system functionalities: Firstly, by introducing AI deep learning algorithms to enhance the system's predictive capabilities for complex risk scenarios; Secondly, by expanding the system's application scenarios to enable full lifecycle monitoring throughout the bridge construction and operational maintenance phases; Thirdly, by optimizing the system's hardware integration solutions to develop compact, low-power, high-precision dedicated sensing devices, thereby reducing deployment costs.

Disclosure statement

The authors declare no conflict of interest.

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Central Air Conditioning Engineering Design for an Office Building in Shenyang

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Abstract: Located in Shenyang (Cold Zone C), this office building is a high-rise structure consisting of 1 basement floor and 9 above-ground floors, with a total height of 48.15 meters and a building area of 28,616.2 m^2. It serves as an enterprise office building. The design aims to maintain an indoor temperature of 26 °C (60% relative humidity) in summer and 18 °C (50% relative humidity) in winter. Using Tianzheng HVAC calculations, the total cooling load is determined to be 1,501.09 kW (with an index of 113.32 W/m^2), and the total heating load is 1,454.72 kW (with an index of 109.8 W/m^2). System scheme: The ventilation system utilizes fresh air ducts to transport fresh air. Offices and similar spaces employ fan coil units combined with an independent fresh air system (with square diffusers for air supply from above and return air from below, and single-layer louvered return air outlets). Lobbies, ball game rooms, and similar spaces utilize an all-air system (with swirl air outlets for air supply and single-layer louvered return air outlets for return air). The water system in this design employs a closed, return-flow, two-pipe, primary pump system. The cold source equipment is selected as two water-cooled screw chillers (LS850H), while the heat source is connected to the municipal heat network (110/60°C) and exchanges heat through a BR0.2 heat exchanger. Equipment selection includes: chilled water pump ISG-125-200B, cooling water pump IS100-65-315C, and hot water pump IS100-65-315; the pressure maintaining and water replenishing equipment adopts a pressure tank V2-500-460 and a water replenishing pump ISG40-250; the water treatment equipment includes a softened water tank FRP-1.6, a DH-1 type softened water processor, etc. Energy conservation and protection: Equipment is equipped with soft hoses and shock absorbers for noise and vibration reduction; pipelines are insulated with foam rubber or centrifugal glass wool, and air ducts are protected against corrosion with epoxy zinc-rich primer and polyurethane topcoat. Condensate water pipes are protected against corrosion with PVC plastic pipes.

Keywords: Shenyang; Office building; Central air conditioning; Design

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1. Introduction

Currently, some central air conditioning systems in office buildings in Shenyang face issues such as high energy consumption, insufficient system compatibility, and low heating efficiency in winter, making it difficult to balance energy conservation and comfort requirements [1]. Against this backdrop, combining the climatic characteristics of Shenyang with the functional requirements of office buildings, conducting research on central air conditioning engineering design, optimizing system selection and design schemes, is of great practical significance for reducing building energy consumption, improving the quality of the office environment, and promoting regional building energy conservation development. It also provides a reference for the design of central air conditioning systems in similar cold regions.

2. Project overview

The building is located in Shenyang, which falls within the cold zone of the thermal engineering division, specifically the severe cold (C) zone. The winter cold period is relatively long, while the summer period is shorter. The building type is a high-rise structure with a fire resistance rating of Grade I. The building serves as an enterprise office building, with the main rooms being offices, followed by archives rooms, conference rooms, and other such spaces. The total land area of the project is 19,998.57 m^2; the total construction area of the office building is 28,616.2 m^2, including 20,582.62 m^2 of aboveground construction area and 8,033.58 m^2 of underground construction area. The building has one basement floor, nine aboveground floors, and two podium floors, with a total height of 48.15 meters [2].

The cold and heat sources for this design utilize the municipal heating network and chiller units. The air conditioning system scheme for the designed area employs a fan coil unit plus fresh air system and an all-air system. The cold and heat source room is located in an independent room on the basement floor, while the cooling tower is situated on the roof.

3. Air conditioning system design

3.1. Air conditioning design parameters

3.1.1. Outdoor meteorological parameters

Table 1. Outdoor calculation parameters for air conditioning in Shenyang

Outdoor environmental design	Parameters
Calculated daily average temperature for outdoor air conditioning in summer	27.5 °C
Calculated dry bulb temperature for outdoor air conditioning in summer	31.5 °C
Calculated wet bulb temperature for outdoor air conditioning in summer	25.3 °C
Average outdoor relative humidity in summer	65%
Outdoor atmospheric pressure in summer	100090 pa
Maximum wind direction and average wind speed in summer	2.6 m/s
Calculated temperature for outdoor heating in winter	-5.2 °C
Calculated temperature for outdoor air conditioning in winter	-20.7 °C
Calculated temperature for outdoor ventilation in winter	-11 °C
Average outdoor relative humidity in winter	60%
Outdoor atmospheric pressure in winter	102080 pa
Maximum wind direction and average wind speed in winter	2.6 m/s

3.1.2. Indoor design parameters

The design temperature for indoor air conditioning in summer is set at 26 °C, while in winter, it is set at 18 °C. The design humidity for indoor air conditioning in summer is set at 60%, and in winter, the design relative humidity is set at 50%. The minimum fresh air volume for each room is set at 30 m^3/h. The values for indoor lighting power density, per capita area, and equipment power density of air conditioning are selected based on relevant design specifications such as the "Standard for Lighting Design of Buildings" GB50034-2013 and the "Standard for Electrical Design of Civil Buildings" GB 51348-2019, combined with common sense.

This office building primarily involves light labor, and it includes a tennis activity room and an activity fitness room where people engage in heavy labor. The working hours of this building are from 8:00 to 18:00, a total of 10 hours. The specific parameters of various types of rooms in this building are shown in **Tables 2**, **3** and **4**.

Table 2. Lighting power density values (W/m^2)

Building category	Room category	Lighting power density (W/m^2)
Corporate office building	Ordinary office	15
	High-end office	18
	Meeting room	11
	Corridor	5
	Hall	15
	Gym	11
	Reception room	15
	Lounge	15
	Private rooms and dining area	13
	Reading room	8

Table 3. Per capita occupied area of different types of rooms (m^2/Person)

Building category	Room category	Per capita area occupied (m^2/person)
Corporate office building	Ordinary office	4
	High-end office	8
	Meeting room	2.5
	Corridor	50
	Hall	2.5
	Gym	8
	Reception room	2.5
	Lounge	2.5

Table 4. Equipment power density of different types of rooms (W/m^2)

Building category	Room category	Power density of electrical equipment usage (W/m^2)
Corporate office building	Ordinary office	15
	High-end office	15
	Meeting room	11
	Corridor	-
	Hall	15
	Gym	10
	Reception room	15
	Lounge	15
	Private rooms and dining area	18
	Reading room	8

3.2. Air conditioning cold and heat source design

Due to the fact that this building is an office building, the total cooling load of the project is 1501.09 kw and the total heating load of the project is 1454.72 kw. Through searching relevant literature and combining with the actual project, four schemes have been preliminarily selected.

After a technical and economic analysis, it is evident that while the cost of year-round air conditioning operation using a chiller unit combined with the urban heat network is relatively high, the initial investment for a ground source heat pump is the greatest, necessitating extensive underground construction. Given that the groundwater level in Shenyang is relatively deep (16–18 meters), this may increase the difficulty and cost of drilling. Shenyang is located in a severely cold region, where the heating efficiency of air source heat pumps decreases significantly as the outdoor temperature drops in winter. Various components of the heat pump system are prone to damage under long-term operation, leading to increased maintenance costs. Considering economic efficiency, the combination of a chiller unit and urban heat network proves to be the most optimal. Therefore, based on a comprehensive comparison, it is recommended to adopt the chiller unit combined with municipal heat sources.

3.3. Air conditioning water system design

For this design, the air conditioning water system employs a closed two-pipe primary pump variable water volume system. An electric two-way valve is installed on the return water branch of the fan coil unit. The system achieves an imbalance rate within 15% between systems by adding balance valves and changing the pipe diameters, and then adjusts through the regulating valves installed on each loop. A flow meter is set up on each floor of the air conditioning water system, and flow meters are also installed on each supply and return pipe of the sub-collector in the refrigeration room. Water hammer prevention measures are implemented between the supply and return pipes of the water pump in the machine room.

Automatic exhaust valves are installed at the highest points and convex bends of the air conditioning water circuit system, while drain valves for cleaning and waterproofing are installed at the lowest points and the bottom of the riser. A whole-process water treatment device is installed on the main pipe of the air conditioning cooling return water system. The air conditioning chilled water and cooling water systems are laid without slope, with a condensate water slope of not less than 3%. Cleanout openings are provided on the condensate water pipes. The pressure bearing capacity of the cooling water and chilled water system pipes and valves should not be less than 1.6 MPa. The refrigeration station is located in the refrigeration room on the basement floor, and the cooling tower is located in the green space at the northwest corner of the building, with one cooling tower corresponding to one chiller unit.

3.4. Air conditioning system design

This design directly selects fan coil units combined with fresh air handling units. The fresh air handling units process outdoor air through cooling, dehumidification, heating, and other processes, ensuring that the enthalpy value of the fresh air entering the unit is equal to that of the indoor air. The fresh air is moved from the outdoor state point W to the indoor state point on the isenthalpic line, where its temperature and humidity parameters are equal to those at point L. At this point, the relative humidity at point L is approximately 90% of the dew point of the machine.

For the lobby on the first floor, the ball activity room and large conference room on the second floor, an all-air system with a primary return air system is adopted.

4. Selection of cold sources and related equipment

4.1. Determination of the refrigeration room

The architectural engineering project designed this time has the available conditions for a basement. Based on the design principles of saving building space and optimizing layout, after comprehensive argumentation, the refrigeration and heat exchange room is located on the first basement floor [3].

When selecting a refrigeration unit, it is necessary to comprehensively consider the purpose of the building, the characteristics of various refrigeration machines, and factors such as local water sources, power sources, and heat sources. The initial investment and operating costs of various types of refrigeration units should be compared through comprehensive technical and economic calculations. In this design scheme, a screw-type chiller unit is selected.

The total installed capacity of the refrigeration machine should encompass the actual cooling capacity required by the user, as well as the cold loss incurred by both the refrigeration system itself and the refrigeration system. Generally, it can be calculated based on the added value. The cold loss is typically 5% to 7% for direct refrigeration systems and 7% to 15% for indirect refrigeration systems. The actual cooling capacity required by the user represents the maximum cooling load for the entire building. Since this building belongs to the indirect cooling system, the added value of cold loss is set at 10%. Therefore, two LS850H refrigeration units are chosen.

4.2. Selection of cooling tower model and quantity

The number of cooling towers should correspond one-to-one with the number of chiller units, and the selection of cooling towers should be based on the cooling water flow rate [4]. Then, the number of cooling towers should be determined based on the calculated cooling water volume and system regulation methods mentioned above. Furthermore, the cooling towers are connected by cooling water pumps, and the number of cooling towers should correspond one-to-one with the number of refrigeration units, with backups being negligible. Therefore, the number of cooling towers selected is two. According to the “Jinri Counterflow Environmental Protection Sheet Metal Cooling Tower Selection Manual”, the model of the cooling tower selected for this project is 10102-GLL.

4.3. Selection of chilled water pumps and cooling water pumps

Select three chilled water pumps with model ISG-125-200B, using them in parallel, with two in operation and one as standby.

Three chilled water pumps of model IS100-65-315C was selected, connected in parallel for use, with two in operation and one as standby.

4.4. Selection of constant pressure water replenishment equipment

This building is a high-rise structure, hence the constant pressure water replenishment device in this design employs a constant pressure device consisting of a pressure tank and a water replenishment pump. Its principle is to maintain the original pressure through volume changes of the pressure tank. The device is composed of a pressure tank, a water replenishment pump, a softened water tank, a softened water equipment, a safety valve, an electromagnetic valve, etc., combined through a piping system, which constitutes the pressure tank constant pressure device. In this design, two water replenishment pumps of model ISG40-250 were selected, with their performance parameters shown in the table below. They were used in parallel, one in operation and one as standby. During water replenishment during the off-season or emergency water replenishment, both pumps operated simultaneously [5].

4.5. Selection and calculation of water treatment equipment

Installing a softened water tank is one of the key measures to optimize the operation of the air conditioning water system. When determining the effective volume of the softened water tank, it is recommended to refer to the flow rate of the make-up water pump for 0.5 to 1.0 hours. According to the previous calculations, the make-up water volume for this system is 1.61 m^3. The make-up water storage volume Vb of the tank was calculated based on the flow rate of the make-up water pump for 1 hour. The pressure relief and drainage capacity of the upper part of the make-up water tank or softened water tank should be able to accommodate a volume equivalent to the maximum expansion of the system.

Check the relevant models of the softened water tank. The selected model was FRP-1.6, and the dimensions of the softened water tank were 1800 × 1200 × 750 (length × width × height).

The fully automatic water softening treatment equipment was selected based on the system's water replenishment volume, and the chosen model was the DH-1 type fully automatic water softener.

Utilizing various complex technologies such as filtration and electrochemistry, it addresses common issues in circulating water systems, including scaling, corrosion, microbial proliferation, and suspended solids pollution. It possesses functions such as scale prevention and removal, sterilization and algaecide, as well as inhibition of microbial proliferation. The comprehensive water treatment device was installed on the main pipes for cooling and chilled water.

In heating, ventilation, and air conditioning (HVAC) systems, solid impurity particles posed a potential threat to equipment, leading to failures such as wear of pump impellers, valve jamming, and blockage of heat exchanger tube bundles. These issues can result in system efficiency degradation at the least, and even downtime accidents at the most severe. Y-type filters precisely filter impurities generated during system operation, such as welding slag, rust, sediment, metal debris, fibers, and colloidal particles, thereby reducing equipment wear and failure, lowering operation and maintenance costs, optimizing system operation efficiency, ensuring stable operating conditions of chillers, stable air conditioning terminal equipment, stable automatic control valves, and stable work efficiency. During system operation, water filters were installed on the inlet pipelines of pumps, heat exchange equipment, and thermal metering devices in air conditioning cold water and cooling water systems to prevent impurities from entering the water system, polluting or blocking these devices. When selecting the model of water filter, the actual diameter of the corresponding pipe section should be considered to ensure a perfect fit between the filter and the pipeline system, achieving the best filtering effect.

5. Selection of heat sources and related equipment

According to the principles of heat exchanger selection, when one heat exchanger stops working, the design heat exchange capacity of the remaining heat exchangers should not be less than 65% of the design heating capacity in cold regions, and should not be less than 70% in severe cold regions. Therefore, the heat exchange capacity of each heat exchanger should not be less than 1120.1 kw. In this design, two BR0.2 heat exchangers are selected, with one in operation and one as standby.

For this design, three hot water pumps with model IS100-65-315, flow rate of 50 m^3/h, and head of 32 mH_2O can be selected and connected in parallel for use, with two in operation and one as standby.

6. Noise elimination, shock absorption, thermal insulation, and corrosion prevention

In every air duct system (including the inlet and outlet of air handling equipment), canvas hoses are installed, with seams fixed using sealant. The water pipe system (chilled water, cooling water) is equipped with rubber flexible connectors, with a length of ≥ 150 mm, and both ends are equipped with limit devices to prevent pulling off. The rigid connection between the cutting equipment and the pipeline is cut off to reduce vibration transmission (vibration isolation efficiency can reach over 80%).

The water pump utilizes an inertial base (with a concrete block weighing 2 to 3 times the equipment) combined with rubber vibration isolators. A 20 mm-thick rubber pad is placed between the base and the ground to further reduce aerodynamic noise and mechanical noise. A series of measures can be taken, such as reducing airflow velocity, selecting low-noise water pumps, and applying sound-absorbing materials

Apply resistive mufflers, reactive mufflers, resonant mufflers, and other types of mufflers, and set up noise reduction plenum boxes (with a size of twice the cross-sectional area of the air duct) at the air supply outlets to reduce airflow noise; add a fiber sound absorption layer at the return air inlet. The fan coil unit adopts a suspended damping spring vibration isolator (with a spring compression of 25 mm), and a rubber pad is added at the connection between the suspension rod and the floor. The condensate water pipe adopts a flexible rubber connecting pipe, and elastic sealing materials are filled at the place where it passes through the floor.

The combination of spring vibration isolator and inertia base is adopted. Inertia base: The thickness of the concrete base is ≥ 500 mm, and its weight is 2 to 3 times that of the unit. The interior is equipped with a steel mesh to lower the center of gravity and evenly distribute the load. Spring vibration isolator: A low-frequency damping spring vibration isolator (natural frequency ≤ 3Hz) is selected. The load capacity of a single vibration isolator is evenly distributed according to the weight of the unit. During installation, it is necessary to level it to ensure even stress distribution.

Flexible foam rubber is selected as the insulation material for small-diameter pipelines, while centrifugal glass wool is chosen for cooling water pipelines and air conditioning ducts.

For air conditioning ducts in civil buildings, a coating scheme consisting of a double-layer epoxy zinc-rich primer and acrylic polyurethane topcoat can be adopted. Freezing water pipes often suffer from condensation due to damaged insulation layers, leading to corrosion. Therefore, plastic-lined steel pipes can be used to replace traditional galvanized steel pipes, effectively isolating moisture from contact with metal. Condensate water pipes, which are in long-term contact with condensate water, are prone to microbial growth and corrosion of the pipes. Therefore, PVC plastic pipes can be selected.

7. Conclusion

This article focuses on the research of the central air conditioning engineering design for an office building in Shenyang. Taking into account the climate characteristics of the severe cold region in Shenyang and the usage requirements of the office building, the core tasks such as system selection, load calculation, equipment layout, and pipeline design have been completed.

During the design process, both energy efficiency and practicality were taken into account, and the parameters of the air conditioning system were optimized. This addressed the pain points of low heating efficiency and high energy consumption in severe cold regions during winter, ensuring that the system meets the comfort requirements of office areas while reducing operating costs. The design scheme presented in this paper is tailored to the actual project and can be directly applied to engineering practice. It also provides a concise and feasible reference for the design of central air conditioning systems in office buildings in Shenyang and similar severe cold regions, successfully fulfilling the research objectives of the thesis.

Disclosure statement

The authors declare no conflict of interest.

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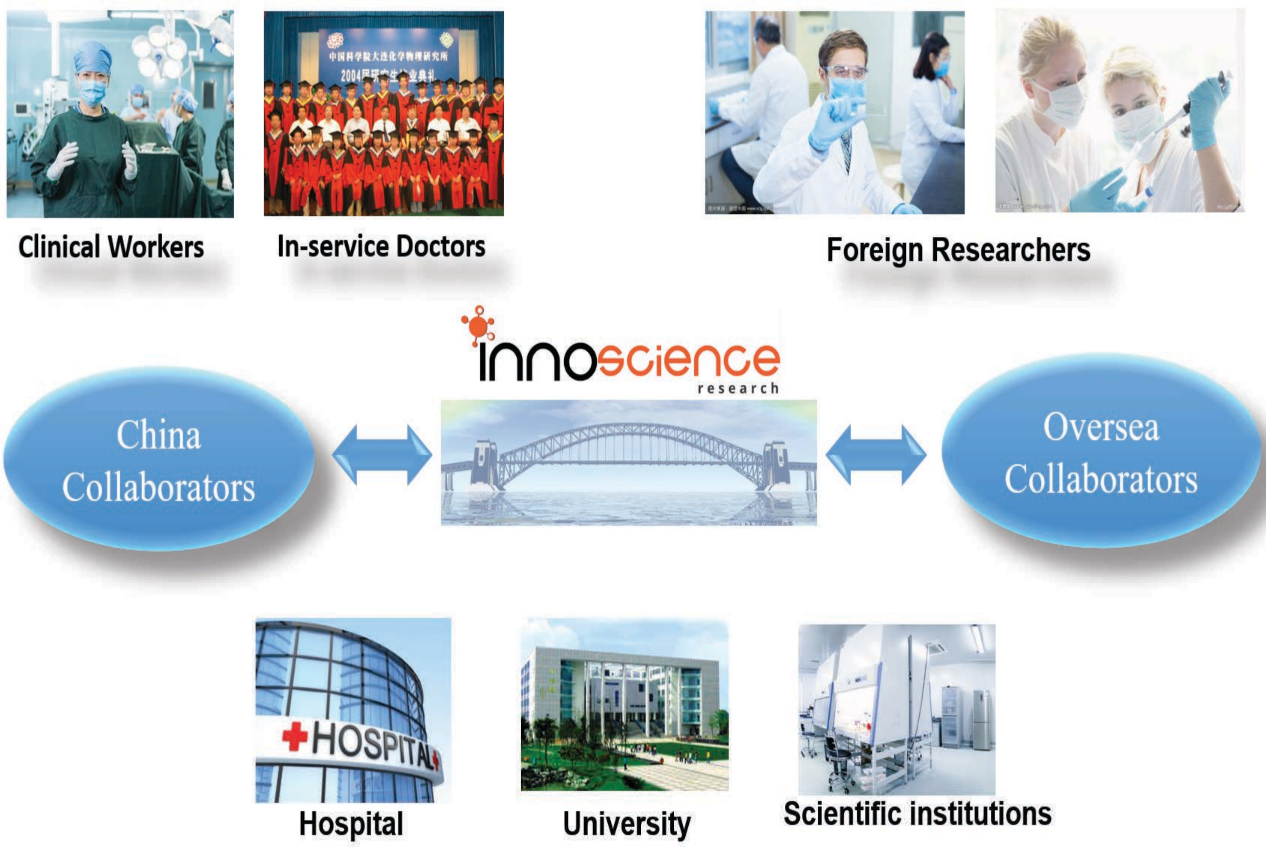

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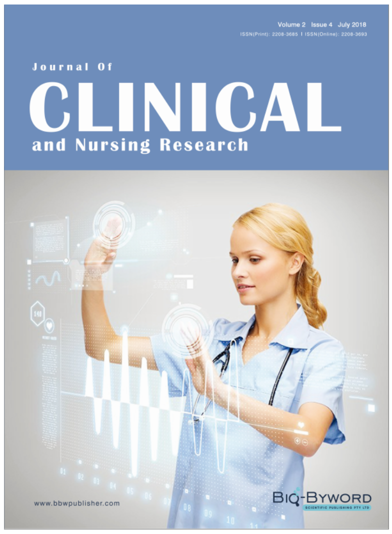

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