Journal of World Architecture

Honorary Editor-in-Chief

Paulina Faria

NOVA University of Lisbon, Portugal

Editors-in-Chief

Alireza Joshaghani

Texas A&M University, USA

Baofeng Li

Huazhong University of Science and Technology, China

BIO-BYWORD SCIENTIFIC PUBLISHING PTY LTD
(619 649 400)
Level 10
50 Clarence Street
SYDNEY NSW 2000

ISSN (ONLINE): 2208-3499
ISSN (PRINT): 2208-3480

Journal of World Architecture

Focus and Scope

The *Journal of World Architecture* is a peer-reviewed international journal, which offers an avenue for researchers and practitioners to present the latest progress associated with architecture, occupants and related policies. It aims to encourage academic exchange and enhancing professional development in this field.

Topics covered but not limited to:

- Architecture theories and practices of design, technology and construction;
- Impacts of architecture on society, economy and environment;
- Analysis of occupants physically and psychologically and the application of new technologies, materials to meet their needs;
- Formulation of public policy as well as organisational structures and networks.

About Publisher

Bio-Byword Scientific Publishing is a fast-growing, peer-reviewed and open access journal publisher, which is located in Sydney, Australia. As a dependable and credible corporation, it promotes and serves a broad range of subject areas for the benefit of humanity. By informing and educating a global community of scholars, practitioners, researchers and students, it endeavours to be the world's leading independent academic and professional publisher. To realize it, it keeps creative and innovative to meet the range of the authors' needs and publish the best of their work.

By cooperating with University of Sydney, University of New South Wales and other world-famous universities, Bio-Byword Scientific Publishing has established a huge publishing system based on hundreds of academic programs, and with a variety of journals in the subjects of medicine, construction, education and electronics.

Publisher Headquarter

BIO-BYWORD SCIENTIFIC PUBLISHING PTY LTD
Level 10
50 Clarence Street
Sydney NSW 2000
Website: www.bbwpublisher.com
Email: info@bbwpublisher.com

2025, Volume 9, Issue 3

Table of Contents

1 **Strategies for Route Design in Highway Reconstruction and Expansion Projects**
Jianning Si

7 **Research on Innovative Design of Rural Education Practice Base in Longhe Town, Fengdu County**
Yuan Zhang, Ni Lan, Feng Huang, Yuan Sun

16 **A Research on the Practical Approach of Cultural and Creative Design to Tell Chinese Stories Well in the Context of Digital Media— Taking Haikou Qilou as an Example**
Bo Yuan

23 **Discussion on Traditional Residence Remodeling and Renewal Design Pointing to Green Building System--Take Wanggezhuang Traditional Residence as an Example**
Ziying Li

29 **Research on the Integration Path of Practical Teaching and Education in Civil Engineering and Transportation Majors Oriented by Employment**
Lei Zou, Lixin Li

36 **Research on the Intelligent Design and Management of Buildings Based on the Internet of Things Engineering**
Fan Wang

43 **Renewal Design of an Urban Heritage Park: The Case of King Yu's Terrace Park**
Qianqian Zhang, Ziyuan He, Kaiwen Sun

55 **Numerical Simulation of M-Shaped Multi-Row Pile-Supported Foundation Pit Excavation Based on ABAQUS**
Meng Chen, Chuanteng Huang, Shuang Pu, Jilun Cai, Zuocai Li, Yufu Huang

64 **Research Progress on Risk Assessment in Construction Sites**
Shoujuan Cui

72 **An Intelligent Vibration System for Concrete in Nuclear Power Engineering**
Yuzhong Han, Shiliang Ji, Pu Chen, Yulin Liu , Weihong Dong, Pengyu Zhang

79 **Finite Element Simulation of Mid-Joints in Chuandou-Style Tenon-Mortise Connections of Dong Drum Towers in Guizhou Based on ABAQUS**
Ziquan Jiang, Shuang Pu, Chuanteng Huang, Jilun Cai, Junxiu Liu, Hongyao Tang

89 **Research on the Application of BIM Technology in the Architectural Design Phase**
Ying Lin, Juan You

95 **Analysis of the Application of Mechanical and Electrical Equipment Supporting Technology in Coal Mine Filling Mining Face**
Sanmin Wang

102 **Research on the Construction Path of the Training Model for Applied Talents in the Architecture Major of Universities in the New Era**
Huinan Liu, Yukang Cheng

109 **BIM Application in Road Construction Sector of Developing Countries**
Shuxing Kang

116 **An Exploration of Garden Art in "A Dream of Red Mansions"**
Youjun Tang

125 **Design and Finite Element Analysis of Smart Lining Trolley for Plateau Railway**
Yuan Wang

134 **Real-time Monitoring and Alarm Strategy for Construction Site Safety Based on the Integration of BIM and AI**
Ying Peng, Huiming Qin, Lianyuan Peng, Taolin Luo, Baoming Dai, SiyanYu, Yifei Xu

141 **Research on the Application of Local Materials in the Environmental Design of Rural Kindergartens**
Liping Qin, Baoxia Yu

146 **Research on Multi-functional Excavation Trolley for Single-track Tunnel Face**
Guangming Zhang

159 **Research on the Optimization and Simulation of Assembly Line Balancing Based on Improved PSO Algorithm**
Wenkang Zhang

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Strategies for Route Design in Highway Reconstruction and Expansion Projects

Jianning Si*

China Merchants Chongqing Communications Technology Research & Design Institute Co., Ltd., Chongqing 400067, China

**Author to whom correspondence should be addressed.*

Abstract: Due to the substantial and continuous growth of transportation demand in China, the existing highway capacity has become insufficient to meet the increasing traffic volume. The implementation of highway reconstruction and expansion projects has gradually become a key measure to improve the service level of the road network and alleviate traffic congestion. Meanwhile, route design is a core aspect of highway reconstruction and expansion projects, and its scientific nature and quality can directly affect the safety, economy, and future operational efficiency of the highway. Therefore, this article provides a detailed analysis of the principles and requirements of route design for highway reconstruction and expansion projects. Additionally, it delves into the design process and key technologies applied in route design for these projects.

Keywords: Highway; Reconstruction and expansion projects; Route design

Online publication: July 1, 2025

1. Introduction

Based on the analysis and research of current highway traffic data, traffic volume is expected to continue to grow in the future. Consequently, issues such as poor highway safety, frequent accidents, and inadequate transportation performance will gradually emerge, making it difficult to effectively meet the needs of socio-economic development, traffic volume, and social service levels. Therefore, it is necessary to reconstruct and expand the current highways to repair and widen them. However, during the route design process, it is essential to fully consider geological conditions, economic conditions, and topographical conditions. Additionally, optimal design plans should be selected through performance evaluation and comparison to establish a solid foundation for the sustainable development of highways in the future.

2. Principles of route design for highway reconstruction and expansion projects

2.1. Efficiency

Improving efficiency is a crucial principle in route design for highway reconstruction and expansion projects. Therefore, during the actual design process, relevant staff must carefully analyze and consider various factors such as vehicle types, traffic flow, and road conditions. Based on this analysis, they should scientifically plan the design route to significantly enhance the transportation efficiency and capacity of the highway. Additionally, designers and staff should fully consider the interchangeable design and layout of the route to provide better travel conditions for people, thereby greatly improving the level of highway transportation [1].

2.2. Safety

Safety is also an extremely important principle in the route design process for highway reconstruction and expansion projects. As highways currently serve as critical transportation corridors between cities, the safety of these projects provides strong protection for the lives and property of travelers. Therefore, during the route design process, staff must carefully analyze and consider the safety level of the route. Only by doing so can they minimize safety incidents caused by issues such as sharp bends, steep slopes, and tight turns. Additionally, for key highway sections like tunnels and bridges, designers and staff need to adopt effective setup methods to further enhance the safety and carrying capacity of the highway [2].

2.3. Environmental protection

Besides safety and efficiency, environmental protection is another crucial principle in route design for highway reconstruction and expansion projects. Due to the rapid pace of social development in China, people's awareness of ecological environmental protection has significantly increased. As a result, there is growing attention to the damage and impact caused by these projects on the ecological environment. To minimize the destruction of the ecological environment and the occupation of land resources by highway reconstruction and expansion projects, it is essential to choose effective and feasible planning approaches and construction methods. This will better maintain the local ecological balance. Furthermore, targeted environmental protection measures must be taken during the actual construction process to minimize negative effects on the environment, laying a solid foundation for the sustainable development of the project.

3. Requirements for route design in highway reconstruction and expansion projects

3.1. Vertical surface fitting design

When encountering road surface design issues and route intersection problems in the design of highway reconstruction and expansion projects in China, the first step is to apply vertical surface fitting design to achieve good coordination and complete related design work in a timely manner. However, designers and staff also need to further analyze and understand the current situation of the highway to better carry out the reconstruction and expansion design work. Additionally, during the actual design process, it is essential to strictly follow practical needs and objective laws to minimize the safety risks of the reconstruction and expansion project. To significantly reduce design errors and improve design quality, relevant staff must comprehensively analyze and investigate all road conditions related to the reconstruction and expansion, providing strong support for the subsequent development of the highway [3].

3.2. Planar fitting design

When applying planar fitting design to route design for highway reconstruction and expansion projects, relevant staff need to first deal with existing structures and facilities such as highway bridges and tunnels. They must also fully understand the current shape of the highway route and use multi-variable curve fitting methods as the main reference. Additionally, they should reasonably apply circular curves, straight lines, and transition curves to the design of the route to minimize errors within a certain range. During the route design process, it is also necessary to consider the effectiveness and accuracy of the route, as well as its compatibility with the development requirements of modern society. By combining these aspects with planar fitting design, the overall design level and application effect of the highway can be further improved. Furthermore, to significantly enhance the traffic utilization rate of the highway, planar optimization methods can be employed. Finally, designers and constructors also need to consider the safety and comfort of people's travel. Therefore, it is necessary to continuously improve the accuracy of design and construction work from the aspect of detailed design, so that drivers can travel on the highway under safe and stable conditions [4].

3.3. Linear design

During route design, it is essential to fully consider various issues arising from the reconstruction process and approach all challenges with a positive attitude. Linear problems in highway design are a relatively common cause of accidents. Therefore, continuously optimizing and improving linear design is crucial to better ensure people's travel safety. Additionally, designers need to analyze and study other common accidents to identify their root causes and propose targeted solutions. Furthermore, designers should place warning signs at appropriate locations on the highway, allowing drivers to timely understand the road conditions, prepare mentally, and heighten their vigilance, thereby effectively ensuring people's travel safety.

4. Route design process in highway reconstruction and expansion projects

4.1. Research and survey

Firstly, it is necessary to carry out research and survey work for route design, which is a very important step in the planning and design process. Designers must fully understand various natural factors related to the entire project, such as hydrology, geology, and climate. Moreover, it is equally crucial to comprehend the social and human conditions as well as the ecological environment surrounding the project. Designers and constructors also need to identify potential risks and issues, such as ecological damage and geological disasters, to better address problems in subsequent planning and construction. Additionally, during the research and survey work, designers can apply advanced technological means such as Geographic Information Systems, remote sensing technology, and total station surveying technology to provide strong support for related scheme design work [5].

4.2. Scheme design

After completing the preliminary research and survey work, it is time to proceed with the scheme design. Due to its complexity, scheme design is a critical aspect of highway reconstruction and expansion project design. During the design process, staff need to comprehensively analyze and integrate various data obtained from the previous stage. Simultaneously, they must consider multiple factors such as the human environment, natural environment, and economic factors to propose various possible design schemes. These schemes involve route selection, changes in technical means, adjustments to environmental protection measures, and more. Furthermore, during the scheme design process, it is necessary to fully utilize the imagination and creativity of the designers while considering the feasibility of real-world conditions and technology, striving to be reasonable, evidence-based, and measured in approach. **Table 1** shows specific design schemes.

Table 1. Design schemes for highway reconstruction and expansion projects

Expressway name	Original plan	Reconstruction and expansion plan	Expansion method
Jingbin Expressway	Two-way four lanes	Two-way six lanes	Bilateral widening
Fokai Expressway	Two-way four lanes	Two-way eight lanes	Bilateral widening
Fuxiajin Expressway	Two-way four lanes	Two-way eight lanes	Bilateral widening
Huning Expressway	Two-way four lanes	Two-way eight lanes	Bilateral widening

4.3. Evaluation

If designers develop multiple design schemes, a comprehensive analysis and discussion of each scheme are required. This mainly involves aspects such as economic rationality, technical feasibility, ecological environmental impact, and social impact. When evaluating the technical feasibility of a design scheme, it is essential to clarify the project's construction quality, construction difficulty, and safety factors. When assessing the economic rationality of a design scheme, research and consideration of investment benefit analysis and project cost estimation are necessary. Additionally, when evaluating social impact, an analysis of industrial development and the lives of local residents should be conducted. This provides a strong basis and support for clarifying subsequent design schemes [6].

4.4. Scheme clarification

After comprehensively analyzing and evaluating various planning schemes, an optimal scheme is selected. This optimal scheme should consider social, technical, ecological, and economic aspects, aiming to find a balanced development plan. Additionally, it is necessary to consider relevant policies, laws, and planning standards in China to ensure that the finally selected scheme aligns with Chinese laws and regulations and actual needs. During the final selection process, relevant departments and experts should jointly analyze and discuss the options, actively listen to suggestions from various parties, and ultimately choose the most suitable scheme.

5. Key technologies applied in route design for highway reconstruction and expansion projects

5.1. Intelligent transportation technology

In recent years, advanced intelligent transportation technology in China has matured and is gradually being widely applied in route design for highway reconstruction and expansion projects. The increasingly significant role of intelligent transportation technology is primarily achieved through methods such as intelligent traffic signal control systems, intelligent traffic management systems, and vehicle autonomous driving technology. These methods enable real-time monitoring of traffic flow, which helps designers obtain more accurate and abundant traffic flow data during the design phase. Additionally, useful information obtained through these intelligent transportation technologies can assist designers in determining parameters such as highway ramp settings, vertical and horizontal sections, and the number of lanes. The application of intelligent transportation technology can also comprehensively evaluate all design schemes through methods like traffic simulation, thereby significantly improving the overall project quality [7].

5.2. Geological and topographic map production technology

Geological and topographic map production technology plays a crucial role in route design for highway reconstruction and expansion projects. The application of this technology can provide critical parameters and information for related engineering planning and design work. It also helps designers understand the highway's stratigraphic lithology, geological structure, seismic activity, and other relevant details, allowing them to determine appropriate road planning strategies based on actual conditions. Furthermore, the use of topographic maps can fully reflect local terrain features such as elevation, river valleys, and land types, which serve as important guides for route design work. Recognizing that the quality of geological and topographic maps directly affects the scientificity and effectiveness of highway design, existing rapid mapping methods primarily include satellite remote sensing technology, aerial photogrammetry technology, and LiDAR technology [8]. The application of these technologies enables the rapid collection of vast amounts of geographic information, providing excellent technical support for the generation of geological and topographic maps. Additionally, research on geological and topographic maps is gradually deepening, ensuring that engineering design schemes are more comprehensive and detailed.

5.3. Remote sensing and geographic information technology

The application of remote sensing and geographic information technology in route design for highway reconstruction and expansion projects can bring new ideas and techniques to related design work. Remote sensing technology enables the acquisition of geographic information data with higher resolution and a broader range, laying a solid foundation for spatial information planning in the entire project. Additionally, geographic information technology effectively integrates large amounts of diverse geographic information, analyzes, processes, and displays it, serving as a valuable tool for efficient information processing and spatial analysis in engineering decision-making. Furthermore, the use of remote sensing and geographic information technology in the survey and design phase can effectively facilitate tasks such as land use classification, topographic mapping, and environmental studies. It also allows for the establishment of a comprehensive geographic information database, which not only provides an important reference for route design but also fully meets the needs of engineering construction monitoring and environmental protection [9].

6. Conclusion

Route design for highway reconstruction and expansion projects is relatively complex, involving multiple fields such as transportation, engineering, and the environment. During the design process, it is essential to conduct thorough preliminary research and analysis, strictly follow basic principles such as safety, efficiency, and environmental protection, and adopt scientific and reasonable route design strategies to further optimize and improve vertical surface fitting design, planar fitting design, and linear design. Simultaneously, advanced technologies such as intelligent transportation technology, geological and topographic map production technology, remote sensing, and geographic information technology are applied in route design for highway reconstruction and expansion projects. This significantly enhances the traffic capacity and service level of the highway, providing strong support for regional economic development and enabling the highway to better adapt to future traffic development needs.

Disclosure statement

The author declares no conflict of interest.

References

[1] Yuan H, 2024, Drainage Measures for Highway Reconstruction and Expansion Projects Based on Route Design. Transportation World, 2024(4): 139–141.

[2] Song Y, Zhang H, 2024, Route Alignment Fitting Method for Beijing–Taiwan Expressway Reconstruction and Expansion Project. Heilongjiang Transportation Science and Technology, 47(6): 13–16.

[3] Zhang Y, 2021, Design Method of Highway Reconstruction and Expansion Route – Taking the Shuikou–Baisha Section of Shenyang–Haikou National Expressway as an Example. Engineering and Technological Research, 6(18): 218–219.

[4] Hou B, 2021, Analysis on the Key Points of Route, Subgrade, and Pavement Design for Highway Reconstruction and Expansion Projects. Architecture and Decoration, 2021(24): 193–195.

[5] He B, Zeng L, Li J, 2023, Highway Reconstruction and Expansion Route Scheme Based on Multi-Factor Constraints and Centerline Offset. Guangdong Highway Traffic, 49(2): 6–10.

[6] Liao L, Ji G, 2023, Discussion on the Overall Design Scheme of the Reconstruction and Expansion of Shenyang–Heao–Shenzhen Airport Expressway. Construction Machinery, 2023(10): 115–121.

[7] Fu W, Ma Z, Li K, 2021, Research on Overlay Design for Highway Reconstruction and Expansion Considering Road Alignment Fitting. Highway, 66(10): 97–103.

[8] Yang Z, 2024, Discussion on the Location of Entrances and Exits When the Radius of Convex Vertical Curves Is Insufficient in Highway Reconstruction and Expansion. Railway Engineering Technology and Economy, 39(2): 10–14.

[9] Feng W, 2024, Research on the Design Elements of Routes, Subgrades, and Pavements for the Reconstruction and Expansion of Mountain Highways. Transport Manager World, 2024(26): 37–39.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Research on Innovative Design of Rural Education Practice Base in Longhe Town, Fengdu County

Yuan Zhang, Ni Lan, Feng Huang, Yuan Sun

Chongqing Institute of Engineering, Chongqing 400056, China

Abstract: This study addresses issues in the development of the rural education complex in Longhe Town, Fengdu County, such as the loss of local characteristics, chaotic landscapes, inadequate industrial chains, and fading cultural memories, and proposes solutions. Based on the report of the 19th National Congress, combined with the rural revitalization strategy and industrial integration strategy, through policy analysis, field research, and case studies, a "Five Parks and Two Zones" landscape sequence is proposed to create an experiential, cultural, and educational rural education practice base.

Keywords: Rural education; Intangible cultural heritage; Rural landscape

Online publication: July 1, 2025

1. Introduction

1.1. Project background

In recent years, the Chinese government has attached great importance to agriculture and rural development, introducing various policies to provide policy support for the landscape design of rural education practice bases. The "Rural Revitalization Strategic Plan (2018–2022)" proposes the goals of "implementing rural cultural revitalization and building beautiful villages", requiring the promotion of rural tourism and agricultural leisure development in rural areas. Documents such as the "Guidelines for the Construction of Beautiful Villages", "Overall Planning of Land and Space in Chongqing", and the "Outline of the 14th Five-Year Plan for National Economic and Social Development and the Long-Range Objectives Through the Year 2035" emphasize the development of a green economy, requiring the strengthening of green services for infrastructure and promoting the integrated development of culture and tourism [1]. These policies provide a solid foundation for the construction of the rural education practice base in Longhe Town, Fengdu County.

1.2. Design purpose

(1) Integration of education and agriculture: By combining agricultural activities with education, the aim is to

enhance agricultural education while developing agriculture, aligning with the national "Guidance Outline for Labor Education in Primary and Secondary Schools (Trial)" policy [2].

(2) Inheriting rural culture: Longhe Town is rich in local culture, but it has gradually faded due to reasons such as a lack of promotion and awareness. Therefore, integrating local cultural elements into landscape design aims to preserve rural cultural heritage, create distinctive rural cultural features, and enhance the sense of identity and pride in Longhe Town's local culture.

(3) Promoting ecological environmental protection: The site mainly consists of farmland and small water systems, maintaining a relatively primitive state. Thus, the subsequent design emphasizes strengthening ecological protection, particularly for water systems and farmland.

(4) Advancing rural revitalization: The creation of a rural education practice base aims to promote rural economic development and industrial upgrading, facilitating rural revitalization. Additionally, it integrates and extends favorable resources within and around the site, enabling multi-faceted rural revitalization efforts.

(5) Driving local economic development: By establishing a rural education practice base, the development of local tourism, agriculture, and other sectors is expected to significantly boost local economic income and diversify revenue streams.

1.3. Design significance

(1) Facilitating deep integration of agriculture and education: Designing an education practice-based landscape with agricultural characteristics aims to closely integrate agriculture and education, promoting mutual penetration and fusion. This approach is conducive to expanding the breadth and depth of education, enhancing students' comprehensive qualities and practical abilities.

(2) Preserving and inheriting rural cultural heritage: Incorporating rural cultural elements into landscape design not only preserves and inherits rural culture but also serves as an important pathway for providing rural education to students. This effort aims to foster students' sense of identity and pride in local culture, cultivating confidence in rural culture.

(3) Promoting the popularization of ecological environmental protection awareness: Emphasizing ecological environmental protection in landscape design aims to cultivate students' awareness of ecological environmental protection through green and low-carbon concepts and eco-friendly agricultural environments, thereby advancing ecological civilization construction.

(4) Driving rural revitalization and development: The construction of a rural education practice base is expected to promote rural economic development and industrial upgrading, leading to rural revitalization. This is not only beneficial for rural development and prosperity but also for narrowing the urban-rural gap and achieving integrated urban-rural development.

(5) Providing new educational models and learning methods: This research project aims to offer students a new learning approach and educational model through experiential learning at the rural education practice base. This enables students to better understand and appreciate agriculture, rural culture, and ecological environments, enhancing their comprehensive qualities and practical abilities.

2. Market analysis

2.1. Location analysis

Longhe Town is situated in the heart of the mountainous region on the south bank of Fengdu County. With a total area of 139 square kilometers and cultivated land of 32 mu, it is the largest agricultural town in Fengdu. Rich in natural resources and boasting a long history, the town is built around the Long River (a tributary of the Yangtze River), making it a key location along the river's course. The town is primarily accessible via one provincial road and connected to the outside by a bridge. Internal transportation is divided into four main roads: "First Ring Road", "Second Ring Road", "Third Ring Road", and the riverside road, with the "Second Ring Road" and "Third Ring Road" being the main connecting routes. External transportation options are relatively limited but convenient, while the internal road network is dense and accessible from all directions.

2.2. Natural condition analysis

In terms of natural conditions, Fengdu is located on the Eastern edge of the Sichuan Basin, where the landscape consists of a series of parallel fold systems. The county is characterized by continuous mountains, crisscrossing rivers, and intersecting hills and valleys. The terrain is predominantly mountainous (mountains account for approximately three-fifths of the county's area), followed by hills. Narrow plains are only found in river valleys and between mountains. The alternating distribution of mountains, hills, and plains (or valleys) forms a landscape that is higher in the South and lower in the North, with "four gorges and three valleys." The highest elevation is 2000 meters, the lowest is 175 meters, and most elevations range from 200 to 800 meters. Part of the site features a terraced landscape, typical of terraced fields, while the remaining areas are generally flat, with a maximum height difference of approximately 37 meters.

2.3. Cultural resource analysis

Regarding cultural resources, Longhe Town in Fengdu County is rich in cultural heritage and has a long history. However, cultural inheritance is low, and much of the culture has been forgotten. The surrounding areas of Longhe Town are rich in scenic spots and historical sites. As a necessary path connecting multiple scenic areas, the site experiences high human activity density and good resource conditions. The surrounding infrastructure is complete, and the overall conditions are satisfactory, meeting people's daily needs.

2.4. Visual analysis

In terms of visual analysis, the overall view is relatively cluttered. However, the surrounding buildings are relatively low, providing good landscape views. The site is surrounded by farmland, with a flat terrain, abandoned fields, exposed soil, and overgrown plants. Some houses are in disrepair, and there are noticeable height differences in small parts of the site, forming typical terraced fields.

In conclusion, the overall condition of the site is currently cluttered, and the landscape view is poor. There are some old buildings on the site that require consideration for protection and renovation during the design process. Small parts of the site feature significant height differences and undulations, while the remaining areas are relatively flat. The site and its surrounding areas are rich in culture, but there is a noticeable degree of cultural abandonment and forgetfulness. Additionally, there are a few ancient trees on the site that need to be protected and reused.

3. Design principles

3.1. Feature experiential landscapes

Currently, many rural education practice bases only offer interactivity or leisure activities, with a weak overall experience and few immersive landscapes. Therefore, during the design process, it is essential to focus on enhancing the overall experience of the site, creating experiential landscapes, and integrating local characteristics into the project to create immersive landscapes with local flair.

3.2. Utilize non-material cultural heritage as a supplementary means

Given the historical significance of rural practice education bases and the unique value of non-material cultural heritage, the design should highlight and incorporate local non-material cultural elements. Emphasis should be placed on the utilization, protection, reuse, and innovation of non-material cultural heritage products and traditions, aiming to achieve a distinctive blend of cultural heritage and rural education practice.

3.3. Prioritize cultural education as the fundamental objective

Strengthen the substance of cultural education within the rural education practice base, emphasizing the educational value and purpose brought by rural education. Integrating culture and education allows visitors to experience local culture, its inheritance, and promotion at the rural education practice base, thereby fulfilling its educational significance.

3.4. Focus on rural practice as the core requirement

Enhance rural practices based on the guidelines of the rural education practice base. This involves utilizing local cultural and agricultural products, enabling visitors to engage in activities such as picking, crafting, and processing, to experience the joys of rural life and achieve the core objective of rural practice.

3.5. Adopt safe development as the central criterion

Due to the unique characteristics of rural practice education bases, which often feature varying terrain, water systems, and elevation differences, potential safety hazards may exist. Therefore, it is crucial to understand the local conditions, assess the overall water system and elevation distribution, and install protective fencing in high-risk areas. Regular safety inspections of on-site entertainment facilities, comprehensive emergency plans, and accident prevention measures should also be implemented, adhering to the design philosophy of human-centeredness.

3.6. Implement adaptation to local conditions as the basic premise

In the initial stages of project design, it is essential to conduct a comprehensive understanding and planning of the site, recognizing the unique development characteristics of the project. This is particularly important in protecting local vegetation and ancient trees, which serve as key indicators of adaptation to local conditions. By clarifying the project's theme, incorporating local cultural characteristics, terrain, and social service needs, the development goals can be tailored to the specific context.

4. Design analysis

4.1. Overview of design concept

The project site is primarily characterized by terraced fields and rivers. The design revolves around the landscape design of a rural educational practice base, integrating local intangible cultural heritage, folk customs, and regional characteristics. The goal is to create an educational base that offers experiences, relaxation, and visual enjoyment.

Culture is the soul of the design, tapping into the local customs and traditions formed over generations to allow people to experience farming activities and rural life. With experience as the vitality, the design explores intangible cultural heritage and crafts to create an immersive educational landscape. This enables city residents to experience intangible cultural heritage firsthand, fulfilling the needs for physical and mental pleasure, cultural education, and forming a new industry to boost local economic income.

The design also considers the backdrop of rural revitalization and cultural inheritance, focusing on experiential landscapes to create educational experience spaces. By utilizing local terraced fields and other terrain features, the design aims to create a rustic rural landscape that evokes memories of the site while embodying educational values in the landscape space. This creates a landscape that integrates intangible cultural heritage, cultural education, and rural practice.

4.2. Analysis of design thinking

Guided by site-specific issues, the design establishes rural landscapes, multi-element spaces, and experiential landscapes. This addresses problems such as a lack of diverse activity spaces, the absence of rural landscapes, abandoned buildings, and fading cultural memories.

The design revolves around two main axes: culture and education. The functional structure is dominated by unique experiences and rural landscapes, combining rural revitalization, cultural inheritance, and historical context. This creates a landscape design that integrates intangible cultural heritage, cultural education, and rural practice, embodying the concept of "educating through heritage and reminiscing in the fields."

4.3. Axis analysis

The landscape axis adopts a "Five Parks, Two Zones, Multiple Points" sequence to form a connected landscape.

4.3.1. Five parks

(1) Art park: Constructs an art and culture town based on local intangible cultural heritage and traditional culture.

(2) Rice Park: Features rice as the main crop, utilizing terrain elevation differences to create a rice field agricultural landscape.

(3) Bean Park: Focuses on soybeans as the primary agricultural product, incorporating their processing and sale for an immersive experience.

(4) Folk Park: Reflects the local characteristics of people's livelihoods and life through the concentration of local customs and traditions.

(5) Bamboo Park: Creates a cultural park with ethnic characteristics based on the Gelao culture, descendants of the ancient Yelang people.

4.3.2. Two zones

(1) Rice field viewing area: Offers an enhanced experience and appreciation of rural and farming culture through the landscapes created by rice fields.

(2) Soybean experience area: Allows for the full experience of crop and product processing through various

sales models such as self-picking, self-making, and self-selling. This not only provides agricultural cultural education but also boosts local economic income and enhances participant engagement.

4.3.3. Multiple points

These are the various landscape nodes formed around the five parks and two experience zones.

5. Business model design

5.1. Self-purchased product formats

(1) Direct sales products: Provide high-quality agricultural products such as soybeans and rice directly to customers. These products can be packaged in eco-friendly materials, highlighting their green and healthy features.

(2) Brand story: Create a brand story for the products, emphasizing their cultural and educational value, such as introducing the planting history and traditional farming methods of the products.

(3) Experiential purchase: Although customers can directly purchase products, short experience activities such as tasting freshly made soybean products or rice can also be provided to enhance the shopping experience.

5.2. Participatory product formats

(1) Interactive experience: Design an interactive experience zone where customers can participate in the production process of soybeans and rice, such as planting, harvesting, hulling, and milling.

(2) Educational workshop: Hold educational workshops to teach customers how to make traditional foods using soybeans and rice, emphasizing the cultural and nutritional value of traditional foods.

(3) Customization service: Provide customization services so customers can choose different product formulations or packaging based on their preferences, increasing product personalization.

(4) Souvenir creation: Encourage customers to add personalized markings or designs to the products they make, turning them into unique souvenirs.

(5) Sharing and display: Set up a sharing area for customers to showcase their creations, and provide convenient photo-taking and social media sharing options to increase the social influence of the project.

5.3. Product design combined with education

(1) Curriculum integration: Integrate the product manufacturing process with educational curricula such as agriculture, ecology, and nutrition, providing educational practical activities.

(2) Study tours: Design study tour programs for schools and educational institutions, allowing students to learn agricultural knowledge and traditional culture through hands-on experience.

5.4. Social welfare and poverty alleviation

(1) Designing poverty alleviation paths: Exploring design poverty alleviation paths for collaborative design innovation of the intangible cultural heritage of the Gelao ethnic group, creating a cultural brand with characteristics of the Gelao ethnic group's intangible cultural heritage, promoting the revival of intangible cultural heritage operas, opening intangible cultural heritage workshops, and injecting new vitality into the rural economy.

6. Technical implementation

6.1. Project features

(1) Superior geographical location: The project site is surrounded by mountains on one side and water on the other, integrating naturally with the environment to create a unique rural landscape. This provides excellent natural conditions and site characteristics for carrying out rural education practices.

(2) Deep cultural heritage: The site contains many old buildings and stilt houses, rich in historical and cultural connotations. Combining local intangible cultural heritage and rural customs, it can add a unique cultural atmosphere to the project and attract more tourists and participants.

(3) Diversified educational experience: The project design combines unique experiences, rural landscapes, and rural revitalization, integrating cultural inheritance, historical context, and rural practices. This provides participants with a rich and colorful experience of intangible cultural heritage and learning opportunities, promoting the inheritance and development of cultural education.

(4) Sustainable development: In improving the current situation, enhancing cultural and diversity aspects, environmentally friendly and energy-saving technologies, as well as intelligent sensing technologies, can be used to build a green and sustainable rural education practice base. This supports local rural revitalization and sustainable development.

(5) Highlighting local characteristics: Through in-depth research on the internal conditions, advantages, crops, and vegetation of the site, combined with human customs, a rural education practice base with distinct local characteristics can be created. This enhances the project's visibility and attractiveness, injecting new vitality into local economic and cultural development.

6.2. Innovations

(1) Injecting vitality into the integration of education and agriculture: By combining agricultural activities with education, agricultural education is strengthened while developing agriculture. This can also be synchronized with the "Guidance Outline for Labor Education in Primary and Secondary Schools (Trial)" policy launched by the country [3].

(2) New inheritance of old culture: Longhe Town is rich in various local cultures, but some, such as the Gelao sacrificial altar culture, have gradually faded due to lack of promotion and awareness. Therefore, integrating local cultural elements into the landscape design, inheriting the rural Gelao cultural heritage, and creating a rural intangible cultural heritage feature can also enhance the sense of identity and pride in Longhe's local culture [4].

(3) Utilizing new energy to promote green environmental protection: Adopting environmentally friendly and energy-saving technologies in project construction, such as solar power generation systems and rainwater collection and utilization systems, reduces the consumption of natural resources and creates a green and sustainable rural education practice base.

(4) Advancing rural revitalization: The creation of a rural education practice base helps promote rural economic development and industrial upgrading, facilitating rural revitalization. Additionally, it allows for the integration and extension of favorable resources within and around the site, enabling multi-faceted rural revitalization.

(5) Boosting the economy through new landscape design: By building a rural education practice base, it drives local economic development, particularly in tourism and agriculture, thus increasing local economic income in multiple ways.

(6) Introducing new technologies into design: Applying virtual reality technology to design a virtual scenic area navigation system provides participants with an immersive experience, showcasing the history, characteristics, and stories of intangible cultural heritage and rural landscapes [5]. Simultaneously, virtual reality technology can be utilized to develop interactive education projects, enhancing participants' learning effectiveness and experience [6].

7. Conclusion

This project will further study the internal conditions, site advantages, vegetation situation, and human customs of the site. It aims to improve the current situation, enhance the site's cultural and diversity aspects, and create an experiential, cultural, and educational countryside. This will promote the deep integration of agriculture and education, protect and inherit rural cultural heritage, facilitate the popularization and promotion of ecological environmental awareness, drive rural revitalization and development, and provide new educational models and learning methods. Based on this, the project mainly revolves around the two main axes of culture and education. The functional structure is dominated by unique experiences and rural landscapes, combined with rural revitalization, cultural inheritance, and historical context. This creates a rural education practice-based landscape design featuring "heritage fields and learning valleys" with intangible cultural heritage characteristics, integrating cultural education and rural practices.

Funding

Chongqing Institute of Engineering Innovation Training Project: "Yitian Xuegu"–Innovative Design Research on the Rural Education Practice Base in Longhe Town, Fengdu County (Project No.: CXCY2024011); National Innovation Training Project–Landscape Design of Education and Research Base Based on Mine Ecological Restoration - Taking the Restoration of Datukuang in Xinhe Village, Dadukou District as an Example (Project No.: 202312608002X); Chongqing Institute of Engineering School-level Project: Research on Urban Waterfront Landscape Design Based on the Concept of River Ecological Restoration–Taking the Section of Huaxi River in Chongqing Institute of Engineering as an Example (Project No.: 2022xskz02)

Disclosure statement

The authors declare no conflict of interest.

References

[1] Xie K, 2020, Exploration of Terraced Field Landscape Planning in Rural Design. Daguan, 2020(6): 47–48.

[2] Chen W, 2018, Planning of Water Conservancy Scenic Spot with Terraced Fields as the Theme, thesis, Nanchang: Nanchang Institute of Technology.

[3] Chen J, 2022, Research on the Landscape Design of Tourism-Oriented Food Industrial Parks from the Perspective of Intangible Cultural Heritage Live Protection, thesis, Chongqing: Chongqing Jiaotong University.

[4] Li X, 2022, Cultural Tourism Landscape Design of Experiential Landscape. Urbanism and Architecture, 19(14): 196–198.

[5] Chen Z, 2020, Research on the Collaborative Innovation Development of Ethnic Minority Folk Art Industry and Local Economy in Chongqing Ethnic Regions. Art Sea, 2020(11): 158–159.

[6] Zhang Y, 2022, Integration of Traditional Village Landscape Design and Intangible Cultural Heritage Inheritance–Taking Kangjiawei Village in Shaanxi Province as an Example. Modern Horticulture, 45(08): 104–106.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

A Research on the Practical Approach of Cultural and Creative Design to Tell Chinese Stories Well in the Context of Digital Media— Taking Haikou Qilou as an Example

Bo Yuan*

Hainan Vocational University of Science and Technology, Haikou 571126, Hainan, China

**Author to whom correspondence should be addressed.*

Abstract: In the era of rapid development in digital media, cultural and creative design, as an important means of inheriting and disseminating regional culture, faces new opportunities and challenges. This paper takes Haikou Qilou as a case study to delve into the practical approaches of cultural and creative design in telling Chinese stories under the context of digital media. By analyzing the cultural connotations and values of Haikou Qilou and combining the characteristics of digital media, this paper proposes practical strategies in areas such as creative exploration, design expression, and promotion. The aim is to provide a reference for the inheritance and innovation of regional culture in the digital age, and to promote excellent traditional Chinese culture onto broader stages.

Keywords: Digital media; Cultural and creative design; Haikou Qilou; Chinese stories

Online publication: July 1, 2025

1. Introduction

With the rapid development of digital technology, digital media has permeated all aspects of social life, profoundly transforming people's lifestyles and information dissemination models. In the cultural domain, digital media has brought new opportunities for creative design, enabling it to break through traditional forms of expression and limitations in dissemination, presenting the charm of regional culture in more diverse and vivid ways, telling China's stories well. As a unique carrier of Hainan's regional culture, Haikou Qilou is rich in historical and cultural information, witnessing the cultural exchange and integration between Hainan and Southeast Asia. Actions taken to vividly present the Chinese story embodied by Haikou Qilou through creative design in the context of digital media not only helps to protect and inherit the culture of Haikou Qilou but also provides valuable references for the dissemination of other regional cultures.

2. Cultural connotation and value of Haikou Qilou

2.1. Architectural characteristics and historical origins

Haikou's Qilou buildings are mainly concentrated in the old districts of Deshengsha Road, Zhongshan Road, Boai Road, Xinhua Road, Jiefang Road, and Changdi Road [1]. They were built by overseas Chinese who returned from Nanyang in the early 20th century, drawing inspiration from Nanyang's architectural styles. Qilou buildings typically have two to three stories, with the front part of the ground floor being a Qilou colonnade and above the colonnade are the floors [2, 3]. The continuous flow of the Qilou colonnade creates a unique street scene [4]. Their architectural design blends traditional Chinese elements with Nanyang styles, such as the intricate carvings and painted beams of Chinese architecture complementing the latticed windows and pediments of Nanyang, showcasing a distinctive artistic charm [5, 6]. These Qilou buildings are not only typical representatives of modern Hainan architecture but also historical witnesses to cultural exchanges between Hainan and the Nanyang region, bearing witness to the struggles and homesickness of Hainanese people who ventured south [7].

2.2. Regional culture and social life

Haikou's Qilou Old Street is not only a collection of buildings but also a vibrant embodiment of regional culture and social life [8]. It preserves a wealth of intangible cultural heritage, such as traditional Hainan opera performances, the Eight Sounds of Hainan, and other folk arts, along with various traditional handicraft shops like coconut carving, shell carving, and Li brocade production [9, 10]. The commercial atmosphere on the old street is strong, with traditional Hainan snack shops and teahouses scattered throughout [11, 12]. People gather here to enjoy tea, chat, and shop, continuing the lifestyle passed down through generations. The regional culture embodied in Haikou's Qilou, including Hainan's folk customs, traditional skills, and commercial culture, is a testament to the wisdom of the Hainan people and holds immense cultural and social value [13].

3. The influence of digital media context on cultural and creative design

3.1. Expand the space for creative expression

Digital media technology provides rich creative tools and forms of expression for cultural and creative design [14]. Designers can use digital modeling, virtual reality (VR), augmented reality (AR), and animation production to present traditional cultural elements in a more three-dimensional, dynamic, and interactive way [15]. For example, through VR technology, users can experience the historical ambiance of Haikou's Qilou old streets as if they were transported back in time. Using animation production techniques, the evolution of Haikou's Qilou architecture and folk legends can be vividly and engagingly presented in animated form, attracting more audience attention [16]. Digital media technology has broken the two-dimensional limitations of traditional design, expanding the spatial dimensions of creative expression, making cultural and creative design more imaginative and appealing [17].

3.2. Innovative communication mode

In the context of digital media, the channels for disseminating cultural and creative design works have become more diversified and convenient [18]. The widespread use of the internet allows information to spread globally in an instant, making social media, video platforms, and digital museums key platforms for the dissemination of cultural and creative design works. Compared to traditional methods, digital media dissemination is characterized by immediacy, interactivity, and precision [19]. Users can interact with works through likes, comments, and shares, while communicators can promptly adjust their strategies based on user feedback, achieving precise targeting. For example, posting Haikou Qilou cultural and creative design works on social media platforms can quickly attract a large number of users' attention and discussion, generating topic heat and thus expanding the reach and influence of the culture [20].

3.3. Meet the needs of multiple users

The development of digital media has made users' demand for cultural and creative products more diverse and personalized. Users of different ages, genders, and regions have varying needs for such products. Digital media can use big data analysis and other technologies to gain deep insights into users' interests, consumption habits, and other information, providing them with personalized cultural and creative products and services. For example, for young user groups, mobile games and anime merchandise themed around Haikou's Qilou can be developed to meet their needs for fashion and entertainment. For elderly user groups, digital documentaries and audiobooks about the history and culture of Haikou's Qilou can be produced to help them understand and preserve local culture. The creative exploration of telling Chinese stories well, with Haikou Qilou as an example, in the context of digital media will help to increase the awareness of the people regarding Chinese culture.

4.1. Dig deep into historical stories and folk legends

Haikou's Qilou houses conceal many little-known historical stories and folk legends, all of which are valuable materials for telling China's story well. By consulting historical documents, interviewing local elders, and engaging with cultural scholars, these stories can be deeply explored. For example, understanding the background of the construction of Haikou's Qilou, the arduous journey of overseas Chinese to Nanyang, and the legendary tales that took place in the old streets of Qilou. These historical stories and folk legends should be organized and adapted, integrated into creative cultural designs, making them vivid carriers for cultural dissemination. For instance, historical novels, comics, and short films set against the backdrop of Haikou's Qilou can be created. Through engaging plots and lifelike characters, these works can capture the audience's attention, allowing them to appreciate the history and culture of Haikou's Qilou while enjoying the content.

4.2. Extract unique cultural elements

Haikou's Qilou architecture and regional culture contain numerous unique cultural elements, such as the architectural style of Qilou, decorative patterns, traditional handicrafts, and folk activities. Systematically organizing and analyzing these cultural elements, extracting representative and recognizable ones, can serve as core elements for creative design. For example, incorporating the pediment designs and Chinese window lattice patterns of Qilou into graphic design and product design to develop Haikou-themed cultural and creative products, like postcards, stationery, and home decor items, combining traditional Hainan coconut carving and shell carving techniques with modern design concepts to create innovative crafts. By extracting and applying these unique cultural elements, creative design works can be made more regionally distinctive and culturally rich.

5. Cultural and creative design expression based on Haikou Qilou in the context of digital media

5.1. Digital display and experience design

Using digital media technology to create a digital exhibition platform for Haikou's Qilou, providing users with an immersive experience. Through 3D modeling technology, the old streets of Haikou's Qilou are digitally restored comprehensively. Users can freely explore every corner of the Qilou Old Street via computers, smartphones, VR devices, and other terminals, experiencing its unique architectural style and historical atmosphere. In the digital exhibition, rich information tags and audio guides are added to introduce the historical background, architectural features, and cultural significance of the Qilou, allowing users to gain a deeper understanding of Qilou culture. Additionally, interactive experience segments are designed, such as virtual restoration of Qilou buildings and simulations of traditional handicraft production processes, enhancing user participation and engagement.

5.2. Digital cultural and creative product design

Develop digital cultural and creative products themed around Haikou's Qilou to meet users' diverse needs. For instance, create mobile phone wallpapers, emoticons, and animated posters featuring Haikou's Qilou as the backdrop, making them easily accessible for users to incorporate into daily communication and online sharing. This approach helps increase the visibility and cultural presence of Qilou. Additionally, develop mobile games centered on Haikou's Qilou, integrating its unique architectural features and historical background into the storyline and visual design. This allows users to explore and experience Qilou culture interactively while playing. Furthermore, launch digital artworks related to Haikou's Qilou, such as digital paintings and 3D sculptures, and enhance their artistic and commercial value through online exhibitions and auctions.

5.3. Cross-media narrative design

Using cross-media storytelling techniques to construct a multi-dimensional narrative world of Haikou's Qilou culture. Focusing on the historical and cultural heritage of Haikou's Qilou, this approach involves using various media forms such as films, TV series, animations, novels, and games to tell stories from different perspectives, forming an interconnected and complementary narrative system. For example, start with a documentary about Haikou's Qilou, introducing its historical background and cultural value. Then, build upon this foundation by creating a film or TV series that showcases the lives and emotional stories of people in the old Qilou streets. Simultaneously, develop related animations, novels, and games to further enrich the content and character development. Through cross-media storytelling, attract users with diverse media preferences, expand the audience for Haikou's Qilou culture, and enhance the effectiveness of cultural dissemination.

6. The dissemination and promotion of cultural and creative design with Haikou Qilou as the theme in the context of digital media

6.1. Social media communication strategy

Make full use of social media platforms to promote cultural and creative design works. Create a dedicated official social media account for Haikou Qilou culture, regularly posting content such as cultural and creative design works, historical knowledge, and information about offline activities related to Haikou Qilou. Utilize short videos and live streams to vividly showcase the charm of Qilou culture. For example, invite local residents and cultural experts to host live-streamed tours of Haikou's historic Qilou streets, offering real-time interaction with viewers to deepen engagement. Additionally, produce high-quality short videos showcasing the creation process and practical applications of digital cultural and creative products themed around Haikou Qilou, encouraging users to purchase, share, and further promote Qilou culture. At the same time, collaborate with influencers and major VTubers on social media, inviting them to experience and promote cultural and creative design works of Haikou Qilou, leveraging their influence to expand the reach of the content.

6.2. Online and offline integration promotion

Combining online dissemination with offline activities to form a comprehensive promotional model. Online platforms such as official websites and digital museums can be used to showcase creative design works and historical and cultural materials related to Haikou's Qilou. Additionally, hosting virtual exhibitions, online competitions, and other interactive events can encourage active user participation and engagement with Qilou culture. Offline, host exhibitions of Haikou's Qilou creative design, thematic lectures, cultural festivals, and other activities to display and promote the results of creative design. For example, a creative design exhibition can be held on Haikou's Qilou Old Street, featuring a range of cultural and creative products as well as digital artworks themed around Qilou. Designers and cultural scholars can be invited to deliver thematic lectures, sharing insights into the concepts and approaches behind Qilou-inspired creative design. Through integrated online and offline promotion, enhance the recognition and influence of Haikou's Qilou culture.

6.3. International communication and exchange

Actively promote the international dissemination and exchange of Haikou Qilou cultural and creative design works to let the world appreciate the charm of Chinese regional culture. Utilize international social media platforms and cultural exchange activities to promote Haikou Qilou cultural and creative design works overseas. Participate in international exhibitions, film festivals, animation festivals, and other events to showcase films, animations, and digital art pieces themed around Haikou Qilou, engaging in exchanges and collaborations with international peers. At the same time, establish cooperative relationships with cultural institutions and universities abroad to conduct academic exchanges and talent development programs, jointly advancing the international dissemination and research of Haikou Qilou culture.

7. Conclusion

In the context of digital media, telling the story embodied in Haikou's Qilou through cultural and creative design is of great significance for the protection and inheritance of regional culture and the development of the cultural and creative industry. By deeply exploring the cultural connotations and values of Haikou's Qilou and integrating the expressive potential of digital media, it becomes possible to present the charm of Qilou culture in more diverse, vivid, and impactful ways. This approach can attract broader public interest and participation in the preservation and innovation of regional culture. At the same time, research using Haikou's Qilou as an example provides a practical approach for the development of other regional cultures in the digital age, promoting the global spread and exchange of China's excellent traditional culture, and enhancing the international influence of Chinese culture.

Funding

Philosophy and Social Science Planning Project of Haikou City in 2025 (Project No.: 2025-ZCKT-106)

Disclosure statement

The author declares no conflict of interest.

References

[1] Qin M, Li R, 2024, Design Strategies for Rural Architectural Renovation Under the Perspective of Chan Buddhism Aesthetics. 2024 Interior Design Paper Collection, 2024: 188–192. DOI:10.26914/c.cnkihy.2024.071984.

[2] Zhu S, Liu Q, 2024, Research on Strategies for Enhancing the Spatial Planning of Buddhist Temples Under Chan Buddhism Aesthetics – A Case Study of Guiyuan Chan Temple in Wuhan. Central China Architecture, 42(7): 99–104. DOI:10.13942/j.cnki.hzjz.2024.07.012.

[3] Liu X, Huang S, Bai H, 2025, Study on the Architectural Form Characteristics of Haikou Qilou Old Street. Ancient Architecture and Garden Technology, 2025(1): 100–104.

[4] Hu X, Li X, 2025, Research on the Relationship Between Haikou Qilou Brand Design Development and Cultural Memory. Comparative Study of Cultural Innovation, 9(5): 108–112.

[5] Zhang Y, 2024, Inheritance and Protection of Nanyang Architecture in Haikou From the Perspective of Cultural and Tourism Integration. China Architecture News, China. DOI:10.38313/n.cnki.nzhjz.2024.000213.

[6] Yuan B, Wang Y, 2024, On the Social Aesthetic Value of Haikou Railing. China Architecture News, China.

[7] Yuan B, 2024, A Study on the Tourism Communication Strategies of Haikou Qilou Old Street From the Perspective of Semiotics. Western Tourism, 2024(12): 78–80.

[8] Yuan B, 2024, Research on the Innovative Development of Haikou Qilou Old Street Tourism Under the Background of Semiotics. Western Tourism, 2024(10): 67–69.

[9] He J, Yuan B, 2024, Protection and Renewal Design of Haikou Qilou Historical District From the Perspective of Urban Memory. China Architecture News, China. DOI:10.38313/n.cnki.nzhjz.2024.000137.

[10] Zhou Y, 2024, An Inquiry Into the Decorative Art of Traditional Haikou Arcade Facades Based on Urban Aesthetics Theory. Tian Gong, 2024(7): 27–29.

[11] Xu N, 2023, Analysis of the Decorative Gray Sculptures in Haikou's Qilou and Their Cultural Significance. Jin Gu Cultural Innovation, 2023(41): 85–87. DOI:10.20024/j.cnki.CN42-1911/I.2023.41.027.

[12] Kou K, 2023, A Study on the Experience of Night Tourism Visitors From a Semiotic Perspective – Taking the Old Street of Qilou in Haikou City, Hainan Province as an Example. Western Tourism, 2023(5): 45–47.

[13] Zhang D, 2023, Perception of the Brand Image and Emotional Expression of Tourists in Qilou Old Street, Haikou City, Hainan Province–Based on Online Reviews. Western Tourism, 2023(5): 63–65.

[14] Chen W, Wu X, Wang J, 2023, A Study on the Evaluation of Tourist Satisfaction and Influencing Factors in the Haikou Qilou Historical and Cultural Block. 2023 Collection of Research Papers on Teaching Method Innovation and Practice (Part II), 2023: 110–113. DOI:10.26914/c.cnkihy.2023.022949.

[15] Zhao X, Hu W, 2022, Investigation and Research on the Current Status of Haikou Qilou Renovation. Urban Architecture, 19(15): 154–158. DOI:10.19892/j.cnki.csjz.2022.15.34.

[16] Zhou Y, 2023, Study on the Facade of Haikou Qilou Buildings Based on the Aesthetic Characteristics of Urban Landscape Painting. Tian Nan, 2023(6): 70–72.

[17] Han J, 2023, Research on the Development of Wenchang's Nanyang Architectural and Cultural Tourism From the Perspective of Cultural and Tourism Integration, thesis, Hainan Tropical Ocean University, 2023.DOI:10.27953/d.cnki.ghnhy.2023.000107.

[18] Hao Z, 2023, A Study on the Micro-Renovation and Transformation Design Practice of Zhongjie Road Block in Haikou, thesis, Hainan Normal University.

[19] Wu Q, Ma H, 2023, A Study on the Perception of Haikou's Qilou Old Street Tourism Image by Inbound Tourists Based on Content Analysis. Journal of Taiyuan City Vocational and Technical College, 2023(2): 48–51.

DOI:10.16227/j.cnki.tycs.2023.0105.
[20] Zhang J, Zhu Y, 2022, Rethinking the Regeneration of the Arcade District, Haikou, Hainan. World Architecture, 2022(10): 36–41. DOI:10.16414/j.wa.2022.10.013.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Discussion on Traditional Residence Remodeling and Renewal Design Pointing to Green Building System--Take Wanggezhuang Traditional Residence as an Example

Ziying Li

Qingdao City University, Qingdao City, Shandong 266000 China

Abstract: Since China advocated the conservation of historical and cultural heritage and rural rejuvenation strategy, finding a balance between "protection" and "adaptive use" of traditional villages has become a core challenge for their sustainable development. In November 2023, the Department of Culture and Tourism of Shandong Province announced the list of cultural-ecological demonstration villages and towns in the province, in which Wanggezhuang Street stood out and was awarded the title of cultural-ecological town, becoming a unique representative of Qingdao. This study aims to realize the "harmonious coexistence of multiple interests" by comprehensively examining the current situation of the village through a combination of on-site research, literature analysis, in-depth interviews, and other research methods, supplemented by questionnaires and other means to build a multi-dimensional evaluation system to assess user satisfaction, and then systematically summarize the problems and their root causes of conservation and development. It aims to provide targeted optimization suggestions for village planning, promote the deep integration of traditional village protection and development, achieve a win-win situation for all parties, and contribute to the in-depth implementation of the strategy of rural revitalization.

Keywords: Wangjiazhuang; Traditional houses; Win-win situation; Rural revitalization

Online publication: June 30, 2025

1. Introduction

Driven by the goal of "Carbon Peak and Carbon Neutral", China is accelerating the green transformation of urban and rural construction, and the "14th Five-Year Plan" for cultural development emphasizes "strengthening the protection and inheritance of history and culture, and promoting traditional villages." The "14th Five-Year Plan" for cultural development underscores the importance of preserving and passing down historical and cultural heritage. It calls for enhanced protection and sustainable use of traditional villages, ethnic minority settlements, and towns and villages with historical and cultural significance. Traditional residential buildings are recognized not only as vessels of cultural heritage but also as ecological units. Accordingly, the renovation and upgrading of these structures have evolved from merely improving spatial functionality to a more holistic approach, one that integrates cultural preservation, energy efficiency, and environmental sustainability. How to protect the traditional architectural style, and the continuation of regional cultural genes under the premise of green technology empowered to achieve functional iteration has become an important issue in the field of urban and rural construction.

2. Wanggezhuang Fengshan West community building status quo

Fengshan West Community is located in Wangjiazhuang, Laoshan District. The community houses have different forms, such as single-family houses, three-sided enclosures, villas, etc. Most of the houses were built around thirty years ago and are generally of average quality and appearance. A smaller portion has been renovated or newly constructed in recent years, featuring better construction quality. Among these, the houses used as bed and breakfasts also stand out for their more appealing architectural style. There are also a small number of old houses with gray bricks and tiles built a long time ago, some with damaged walls, some with collapsed roofs, small in size and poor in quality, but the overall preservation of these houses is good and they can be preserved or remodeled for the spirit of the village. Each house looks like an independent work of art when viewed on its own, but it is extremely incongruous when put into the same picture.

Their facades have different shapes, some pursuing modern simplicity, with smooth and cold lines, while others retain their ancient flavor, with carved beams and paintings that show the traces of age. However, the differences in materials exacerbate this sense of incongruity. Some of the walls are made of smooth tiles, reflecting blinding light; some are rough adobe walls, revealing originality and simplicity; and some are mottled wooden structures, with traces of erosion visible. They present different textures and colors under the sun, making the whole village look like an unfinished collage, lacking the harmony and unity it deserves.

This kind of disorderly splicing makes people feel a bit messy, and it is difficult to capture the unique flavor and characteristics of the village, which is also the fundamental problem that exists in most of the traditional houses in China. Therefore, for such a village, how to retain its distinctive advantages while realizing the harmony and unity of the overall appearance will be a topic worthy of deep thought and discussion [1].

3. The meaning of the green building system and Wangjiazhuang traditional residential remodeling methods

A green building system is a comprehensive construction model that takes the concept of sustainable development as the core, and realizes the efficient use of resources, minimization of environmental loads, and health and comfort of human beings in the whole life cycle of a building (design, construction, operation, and dismantling) through the systematic integration of ecological, technological, economic, and socio-cultural elements [2].

Traditional Chinese houses contain regional cultural genes and ecological wisdom, but their spatial functions, material properties, and energy utilization patterns are difficult to adapt to the needs of modern life [3]. As a typical area where mountain and sea cultures meet, Wanggezhuang Street in Laoshan District, Qingdao City, has provided an innovative sample for the construction of sustainable human settlements in the context of rural revitalization by adopting the “green building system” as the guide for the renovation of traditional residential buildings, and through the regeneration of functions, upgrading of technology and continuation of culture.

The traditional houses in Wanggezhuang are built along the mountains and the sea, with stone and wooden structures, reflecting the simple ecological concept of local materials and natural ventilation. With “safety as the foundation, culture as the soul, and ecology as the vein”, Wangjiazhuang Fengshan West Community has realized the transformation from a dilapidated residential area to a model of green human settlements through the combination of technological empowerment and traditional wisdom, providing a replicable practical path for the renewal of similar mountain settlements. The following are the methods of remodeling and upgrading Wanggezhuang’s buildings:

(1) Structural safety and ecological restoration at the same time

Located in a mountainous area, the traditional buildings of Fengshan West community are mainly stone and wooden structures, and the transformation needs to prioritize solving the problems of collapsing walls and unstable foundations caused by age and disrepair. According to the professional requirements, the stone walls, beams columns, and other load-bearing components use carbon fiber reinforcement, steel cladding, and other modern technologies to enhance seismic performance, while retaining the original stone texture, to avoid the destruction of the landscape, for the collapse of the stone walls and other hidden dangers, the use of “villagers repair + community support” mode, restoration of the embedded ecological berming technology, and replanting of native vegetation (such as tea seedlings) to stabilize the soil, and the ecological restoration. The restoration is embedded with ecological slope protection technology and replanting of native vegetation (such as tea seedlings) to stabilize the soil, forming a cycle of “restoration-protection-regeneration”.

(2) Functional optimization and spatial activation

To meet the demands of rural tourism, renovations should strike a balance between residential functionality and cultural tourism services. Unused residential houses can be transformed into distinctive bed and breakfasts, preserving the traditional courtyard layout while incorporating shared amenities such as tea rooms and intangible cultural heritage workshops, for example, a Laoshan noodle-making experience area. These upgrades should enhance both cultural display and interactive experiences. At the same time, aging plumbing and electrical systems in the old houses should be modernized, modular sewage treatment technology should be introduced to enable resource recycling, and lighting and drainage systems should be optimized to improve overall living comfort [4]. Optimize lighting and drainage facilities to enhance living comfort.

(3) Integration of local materials and green technologies

Using local stone, bamboo wood, and other renewable resources, artistic reuse of demolished old bricks, tiles, and wooden components (e.g., cultural wall masonry, landscape vignettes), combining the climate characteristics of the mountains and the sea, adopting passive design (e.g., naturally ventilated patios, solar photovoltaic tiles) to reduce energy consumption, and simultaneously introducing an intelligent monitoring system to optimize energy management.

(4) Cultural heritage and industrial development

Cultural protection zones should be clearly delineated, with efforts focused on the repair and preservation of historically valuable old mansions, ancient trees, and traditional handicraft workshops. It is essential to prevent the excessive commercialization that could compromise their original character [5]. Intangible cultural heritage elements, such as Mantis Fist and tea culture, can be artistically reproduced through wall paintings and carvings to reinforce regional identity. Additionally, drawing on the “court-community mediation" model, a collaborative platform should be established involving residents, government, and designers. This platform would help ensure that the renovation process respects the interests of all stakeholders and minimizes potential conflicts. Relying on mountain and sea resources, the project has created a composite eco-tourism node, utilizing the experience of transforming deserted beaches to develop tent camps, eco-trails, and supporting rainwater recycling systems. At the same time, it has combined tea gardens, fruit orchards, and bed and breakfasts, and has designed a picking experience line to form a closed-loop of "lodging-production-consumption" and promote economic development. At the same time, combining tea plantations and orchards with lodging and designing picking experience lines, forming a "lodging-production-consumption" closed loop and promoting sustainable economic development.

4. The green building system of the traditional residential transformation and its renewal design strategy

(1) Material green transformation

On the application of locally sourced and renewable materials, mountainous areas can directly mine local stone for wall masonry and floor paving, which not only reduces transportation costs, but also highlights the regional characteristics [6]. In areas with abundant forest resources, local wood is selected to make beams and columns, door and window frames, while bamboo weaving finishes and straw fiber boards are introduced for indoor wall decorations, and formaldehyde-containing materials such as plywood are used less frequently. On the recycling of old materials, after cleaning and repairing the dismantled green bricks, the staggered collage can be used to create a characteristic cultural wall. The old timber will be sanded and polished for the production of furniture or porch shelves. When new energy-saving materials are replaced, in the cold northern regions, 50 mm-thick rock wool boards can be added to the outside of the original walls, and moisture-proof treatment can be done [7]. In the hot and humid regions of the south, vacuum insulation boards are laid on the roof, which can effectively block the solar radiation heat from being transmitted into the room and significantly reduce the frequency of air conditioning use.

(2) Energy system optimization

In terms of solar energy utilization, in residential houses with suitable roof slopes and no shade, monocrystalline silicon solar photovoltaic panels are installed, combined with energy storage devices to store excess electricity for nighttime use; at the same time, split solar water heaters are set up, with the collector panels mounted on the roof and the tanks placed indoors, to ensure a stable supply of hot water [8]. In the design of natural ventilation and lighting, the location and size of doors and windows are adjusted through computer simulation analysis to form a passage through the hall; tiger windows are set on the sloping roof to enhance the ventilation effect and introduce natural light. For areas with cold winters and hot summers, if the geological conditions allow, a ground-source heat pump system is installed, with underground buried pipes in a U-shaped arrangement, absorbing or releasing underground heat through the circulating medium to realize energy-efficient heating and cooling.

(3) Renewal of space function

When optimizing the functional zoning, the hall of traditional houses can be used as the center of family activities, with private spaces such as bedrooms and kitchens set up around it. The attic or mezzanine floor can be used to create a storage area or a leisure study. In the accessibility and aging-adapted renovation, anti-slip ramps are paved at entrances and exits, with slopes of no more than 1: 12 and double handrails installed [9]. Indoor doorways are widened to 900mm to facilitate the passage of wheelchairs and toilets are equipped with toilets, handrails, and emergency call devices. In terms of flexible and variable space design, folding partitions are used to divide the living room and dining room area, which can be completely opened when needed to form open space. Multifunctional sofa beds, liftable dining tables, and other furniture are used to meet the needs of different scenarios of use, and various types of living spaces are divided in detail to fully utilize the limited space to the fullest extent.

(4) Water environment sustainable design

Water environment sustainable design can effectively enhance the utilization rate of water resources, by setting up an underground rainwater collection pool in the corner of the courtyard and installing filters and precipitation devices in the pool, after preliminary purification of the collected rainwater, it can be used for watering courtyard plants through the automatic irrigation system. It can also be set up in the landscape plunge pool to realize the landscape use of rainwater. In terms of sewage purification and reuse, the small sewage treatment device can adopt the biofilm method process, and the treated water is stored in a special tank and used for toilet flushing through an independent piping system [10]. The application of water-saving appliances, the installation of sensor-type faucets, and two-stage flushing toilets, compared with traditional appliances, can save more than 30% of water.

(5) Ecological environment creation

Choosing native tree species for courtyard greening, such as planting *Acacia* and elm trees in the North, camphor trees and banyan trees in the South, and matching flowers such as moonflower and daylily to form a rich plant community. At the same time, setting up rain gardens and utilizing plants and soil to purify rainwater. Vertical greening can be done by planting climbing plants such as creepers and ivy on the exterior walls of the buildings or installing modular green walls. Balconies are arranged with hanging flower pots and planted with herbaceous plants such as mint and *Perilla*, which have both ornamental and practical values. In the ecological landscape design, a small artificial wetland system is introduced, and aquatic plants such as reeds and irises are planted to purify the water while creating a natural and wild landscape atmosphere.

5. Conclusion

Facing the new context of the “dual-carbon” goal and urban-rural integrated development, the transformation of traditional residential buildings needs to further strengthen interdisciplinary collaboration and deepen innovation in material recycling technology, renewable energy application, and community governance model. It is expected that this study can provide a reference for the protection and renewal of more historical and cultural villages, promote the traditional houses from “static protection” to “dynamic regeneration”, and help realize the dual goals of habitat improvement and low-carbon transformation while guarding the cultural roots.

Disclosure statement

The author declares no conflict of interest.

References

[1] Fan W, 2022, Traditional Residence Renovation and Renewal Design Based on Green Building System—The Case of Traditional Residence in Pingyao Ancient City. Beauty and Age (City Edition), 2022(11): 12–14.

[2] Hu C, Li Y, Chen X, 2025, A Study on the Remodeling Design of Traditional Houses in Hedong Village Based on the Theory of Organic Renewal. Beauty and Era, 2025(03): 92–96.

[3] Chong Y, Chen H, 2023, Research on Design Strategy of Organic Renewal and Reorganization of Traditional Residences in Zhongmou County, Henan Province. Chongqing Architecture, 22(5): 17–21.

[4] Yang C, 2024, Research on the Principles and Application Strategies of Green Building Design in China Under the Background of "Double Carbon". China High-Tech, 2024(8): 43–45.

[5] Xu F, 2020, A Study on the Spatial Renewal Method of Traditional Wooden Buildings and Dwellings in Northern Gui—Based on the Project of "Traditional Village Lodging Renovation Design" of the Cross-Domain Work Camp. Artistic View, 2020(7): 126–128.

[6] Wang KX, 2025, Research on Energy-Saving Settlements Based on Green Building Evaluation System—Taking Shanghai Sanxiang Hai Shang Fu Di Project as an Example. Architectural Science and Technology, 9(02): 79–83.

[7] Yang C, Liu Y, Huang D, et al., 2024, Green Building Standard System and Key Technical Measures. Residential and Real Estate, 2024(20): 6–8.

[8] Wen Q, Jiang S, Tang W, 2024, Research on Optimization Strategy of Sichuan and Chongqing Vernacular Building Construction Technology Based on Green Building System. Green Building, 16(2): 29–33+1.

[9] Zheng Y, Zhu H, Lu L, 2024, Construction and Development of Green Building Standard System in Guangxi Under Green and Low-Carbon Requirements. Engineering Construction Standardization, 2024(02): 73–77.

[10] Jiang G, Yuan Y, Xiao T, 2023, Construction and Application of Green Interior Design Strategy System—Taking the New Office Building Finishing Project of a Xiongan Science and Technology Limited Company as an Example. Urban Architectural Space, 30(12): 14–17.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Research on the Integration Path of Practical Teaching and Education in Civil Engineering and Transportation Majors Oriented by Employment

Lei Zou[1]*, **Lixin Li** [2]

[1]Chongqing Energy College, Chongqing 402260, China
[2]Leibo Branch of Sichuan Huichuang Xinhao Mining Engineering Co., Ltd., Sichuan 615000, China

**Author to whom correspondence should be addressed.*

Abstract: To promote the achievement of high-quality and full employment goals for students in higher education, this paper analyzes the integration path of practical education and teaching in civil engineering and transportation majors, guided by surveying employment. This paper proposes three integration paths for practical teaching and education in civil engineering and transportation majors under the employment orientation. The first path is to create a modularized and informatized curriculum system. The second path is to deepen diverse cooperative practices between schools and enterprises. The third path is to construct a diversified quality evaluation system for academic achievement. To ensure the quality of education and employment, schools should continuously evaluate and reflect on the practical effects of these three paths to further optimize them.

Keywords: Civil engineering and transportation major; Employment orientation; Surveying; Practical teaching

Online publication: June 30, 2025

1. Introduction

The civil engineering and transportation industry has always been a pillar industry for national development. In recent years, with the continuous development of information technology, the entire civil engineering and transportation industry is undergoing intelligent transformation, placing higher demands on professionals' expertise and practical skills. However, there have been issues such as outdated course content, insufficient practical teaching time, and low quality of practical teaching in the education of civil engineering and transportation majors [1]. To address these issues, the educational work in civil engineering and transportation majors should determine educational goals based on employment needs, integrate educational resources, and adjust educational methods. This will not only enhance the employability of students in these majors but also provide high-quality talent for the industry's development.

2. Core demands of practical teaching in civil engineering and transportation majors oriented by employment

2.1. Industry and related job demands

Civil engineering is inseparable from surveying and mapping. In the context of large-scale and integrated development of the civil engineering and transportation industry, more diversified surveying technology services are required, giving rise to various surveying technology positions [2]. For example, construction surveyors, BIM engineers, and track inspectors. These positions, as frontline roles in engineering construction, require professionals to have knowledge, abilities, and professional ethics. For instance, surveyors need to have solid knowledge of surveying and civil engineering, and be able to accurately and proficiently use total stations to determine building coordinates. Workers need to master skills such as using BIM software to independently construct 3D building models and perform collision checks. They also need to have the ability to analyze surveying data and identify engineering construction issues.

2.2. Goals for cultivating students' professional abilities

The goals for cultivating the abilities of civil engineering and transportation students under an employment-oriented approach should be derived from the demands of related positions. These goals consist of two parts: the first is technical ability, and the second is professional accomplishment. Technical abilities include basic operational skills, intelligent technology application skills, and data analysis skills. For example, students need to skillfully and standardly use traditional surveying equipment such as levels, with measurement results meeting the national third-level surveying standards [3]. Additionally, students should master drone aerial surveying technology and be able to import aerial survey data into the BIM system for modeling using measured data. Furthermore, students in this major should be able to use tools like Excel to statistically analyze measurement errors and identify abnormal data from a vast amount of information [4].

The goals for professional accomplishment include cultivating students' engineering ethics, interdisciplinary knowledge application skills, and team collaboration abilities. For instance, teachers should make students aware of the impact of distorted or incomplete measurement data on engineering construction and the potential legal consequences of data issues. Teachers should organize virtual experiments and other teaching activities to equip students with methods to address data deviation problems. Moreover, teachers should introduce students to various complex engineering survey projects, guiding them to comprehensively apply professional and interdisciplinary knowledge to analyze and solve problems. During project practice, more emphasis should be placed on cultivating students' team communication and collaboration skills, stimulating their team responsibility and sense of honor [5].

3. Existing problems in practical teaching and education in civil engineering and transportation majors

3.1. Lagging curriculum system

Currently, there are issues with the curriculum system in practical teaching and education for civil engineering and transportation majors. These issues are primarily manifested in two aspects: the separation of theory and practice, and outdated teaching content. For example, schools often divide professional teaching tasks into two independent parts: theory and practice. Theoretical teaching only covers professional knowledge, while practical teaching mainly consists of internships and practical training. Students rarely have the opportunity to learn theory while practicing. Additionally, existing teaching still revolves around main topics such as leveling surveys, angle surveys, and control surveys, with limited coverage of intelligent surveying and mapping technologies like laser point cloud modeling and drone photogrammetry [6].

3.2. Inadequate practice platforms

The nature of civil engineering and transportation courses dictates that teaching must have adequate practical platforms. However, the reality is that some colleges and universities have outdated practical equipment on campus. Old-fashioned optical theodolites and other equipment not only have low measurement accuracy but also differ significantly from the advanced equipment widely used by enterprises. Even the number of old-fashioned teaching devices is limited in some schools. Students cannot fully familiarize themselves with the operational procedures and functional characteristics of the measuring equipment, naturally making it difficult for them to adapt to the work needs of enterprises [7]. Simultaneously, some schools have not established close cooperative relationships with external enterprises, or the management of external bases is loose. During external practices, students often engage in observational learning and cannot participate in core surveying tasks.

3.3. Singular evaluation mechanism

Due to issues with the curriculum system and practical teaching resources, the evaluation mechanism for practical teaching in civil engineering and transportation majors in some schools is singular and rigid. For example, evaluation primarily relies on theoretical examinations, with limited evaluation of students' practical precision and innovation abilities. This type of evaluation not only fails to comprehensively reflect students' professional accomplishment growth but also tends to make students prioritize theory over practice in their learning, ultimately making it difficult to meet the employment needs of enterprises. Simultaneously, most schools have not fully incorporated professional qualification assessments, such as registered surveyors, into their academic quality evaluation mechanisms, resulting in students being unable to benchmark their professional knowledge learning against industry standards.

4. Integration path of practical teaching and education in civil engineering and transportation majors oriented by employment

4.1. Creating a modularized and informatized curriculum system

To address the current issues in practical teaching and education in civil engineering and transportation majors, schools should first establish a modularized and informatized curriculum system oriented by employment. The core of this system is the integration of theory and practice. The system should include the latest industry technologies and knowledge, and it should be progressively layered (as shown in **Table 1**). Each module in the framework should be equipped with corresponding case studies. These case studies not only help students visualize and learn theoretical knowledge but also guide them to reinforce them through practical methods. For example, the theoretical content of measurement errors in the basic module can use several road construction projects as examples. Students can learn to create Excel data record tables through actual road leveling surveys, utilize Excel's data functions to identify abnormal data, and use formulas to calculate critical measurement data such as height differences. Furthermore, advanced modules like BIM technology integration can rely on real-world cases of real-time monitoring and management of project progress and quality using BIM. This allows students to learn how to combine BIM models with on-site collected data to improve project management levels [8].

Table 1. Modularized and informatized curriculum system for civil engineering and transportation majors oriented by employment

Module level	Course content	Skill objective
Basic module	Traditional surveying techniques	Master the standard operations of leveling, angle, and distance measurement
	Surveying error theory	Understand the sources of errors and the principles of precision control
Advanced module	Intelligent surveying and mapping technology (UAV, 3D laser scanning)	Master data collection and initial processing using smart devices
	Integrated application of BIM technology	Achieve collaboration between survey data and BIM models
Innovation module	Comprehensive engineering survey training	Complete the design of full-cycle survey schemes for bridges and tunnels
	Survey data analysis and visualization	Use Python/Excel for deep data analysis

It should be noted that to fully leverage the modularized and informatized curriculum system, professional teachers should also make full use of a combination of virtual and practical in-class teaching methods. For example, blended online and offline teaching, virtual simulation experiments, educational teaching, and project-based learning. Taking virtual simulation experiment teaching as an example, teachers can rely on the existing virtual simulation practice platform for fine adjustment of high-speed rail tracks to provide an immersive simulation of the operating environment for fine-tuning high-speed rail tracks. This gives students the opportunity to familiarize themselves with the craft standards and work details of fine-tuning high-speed rail tracks. Students can practice repeatedly in a virtual environment, enhancing their understanding of the industry and applying professional knowledge to solve complex engineering problems [9].

4.2. Deepening diverse forms of cooperation between schools and enterprises

Deep integration of industry and education allows students to gain a deep understanding of the industry environment and work content, developing professional practical skills and comprehensive literacy in a real-world setting. Therefore, based on the integrated learning of theory and practice in class and on campus, schools should deepen cooperation between schools and enterprises. This provides students with diverse practical opportunities through various forms of school-enterprise cooperation.

Firstly, schools can establish order classes with large state-owned construction enterprises or well-known surveying enterprises in provinces and cities. The teachers in these order classes are professional teachers from schools and technical backbones from enterprises. The syllabus for the order class is developed based on the actual projects of the enterprise, talent needs, and surveying job standards. The teaching content of the order class mainly focuses on real projects, such as precise control network surveying in the construction of new railway lines. The order class adopts a corporate management model, where students automatically receive the title of apprentice upon entering the order class. Students learn professional knowledge from professional teachers and mentors from the enterprise. At the end of each teaching phase, the “dual teachers” evaluate the students’ professional knowledge, practical abilities, and comprehensive professional literacy. The evaluation results are directly converted into titles such as Excellent Apprentice, Group Leader, and Class Monitor. Excellent students from the order class can have priority in joining the partner enterprise after graduation. Alternatively, schools can collaborate with partner enterprises to establish smart surveying and mapping laboratories. The laboratory equipment, such as fully automated total stations and 3D laser scanners, is donated by the enterprise. The laboratory is jointly managed by enterprise engineers and professional teachers. On one hand, schools can organize professional teachers and enterprise engineers to guide students in experimental learning. On the other hand, schools can utilize these advanced devices to provide services such as engineering deformation monitoring and analysis for enterprises. This service-for-resources approach not only addresses the shortcomings of school practical teaching equipment but also meets the actual work needs of enterprises [10].

Secondly, schools can also collaborate with enterprises to create on-campus and off-campus internship bases. The bases are managed in a tiered manner (as shown in **Table 2**). At these bases, students can participate in short-term cognitive internships, such as observing construction sites and understanding the work content of surveying positions. Students can also engage in medium-term skill training, such as hands-on orbit measurement practices. Additionally, students can undertake long-term internships, such as participating in measurement work throughout the entire engineering lifecycle. The internship content for each stage is determined based on the professional teaching content, student needs, and the latest industry developments and technological achievements. Before each internship, students are required to propose at least three theoretical application questions, learn with these questions in mind, and seek advice from enterprise engineers. After the internship, students are required to submit an exploration report and internship reflections.

Table 2. Tiered management approach for school-enterprise internship bases

Stage	Type	Duration	Core content	Ability objective
Basic stage	Cognitive practice	1–2 weeks	Construction site observation, demonstration of typical measurement procedures	Establish understanding of engineering scenes, identify main measurement equipment
Advanced stage	Skill training	4–8 weeks	Sub-skill practical operations (such as track measurement, deformation monitoring)	Master single equipment operation, achieve data accuracy standards
Comprehensive stage	Internship	12–24 weeks	Participate in full-cycle engineering measurements, solve practical problems	Independently complete measurement plans, coordinate multi-team collaboration

4.3. Constructing a diversified academic quality evaluation system

Evaluation plays a crucial role in teaching supervision, adjustment, and motivation. To leverage the power of evaluation, schools should combine outcome-oriented evaluation with process-based evaluation, constructing a diversified academic quality evaluation system. Firstly, schools require students to obtain both academic certificates and professional qualification certificates such as Registered Surveyor and Engineering Surveyor (Level 4) upon graduation. During in-class, on-campus, and school-enterprise practical learning, schools should use the standards for obtaining professional qualification certificates as the overall goal, guiding students to plan their learning direction and develop study plans. Schools can also organize regular competitions such as drone oblique photography modeling to help students improve their skill levels and lay the foundation for obtaining professional qualification certificates. Secondly, schools should transform the requirements for obtaining professional qualification certificates into process-based evaluation items, standards, and methods. For example, students may be required to evaluate themselves by writing internship diaries. These diaries should record daily measurement tasks completed, measurement problems encountered, new ideas for problem-solving, and personal growth in practical operation accuracy.

5. Reflection on the integration of practical teaching and education in civil engineering and transportation majors oriented by employment

As a pilot, Hunan Communication Engineering College and other institutions have already implemented reforms in practical teaching for civil engineering and transportation majors oriented by employment. Through a phase of teaching observation and follow-up surveys of graduate employment situations, it has been found that the new teaching model significantly enhances the employability of students in this major. For instance, the proficiency of graduates in operating measurement equipment has increased by approximately 50% compared to before the teaching reform; the employment rate of students in smart measurement positions has increased by about 35% compared to before the reform. Feedback from enterprises indicates that students trained in the order class can independently undertake small and medium-sized measurement projects in just three months after starting their jobs.

However, there are still some issues with this new practical teaching model. For example, there is a significant shortage of “dual-qualified” teachers, balancing the interests of schools and enterprises is difficult, and quantifying moral education evaluation is challenging. Therefore, when reforming practical teaching methods for civil engineering and transportation majors under the employment orientation, relevant institutions should focus on building a dual-qualified teaching team and expanding the dimensions of practice. For instance, professional teachers could be required to participate in enterprise projects such as bridge inspection and subway measurement quantitatively every five years. Alternatively, technical breakthrough awards could be established to support teachers and enterprises in jointly applying for measurement technology improvement projects. Schools should also actively seek special education funds from education authorities to carry out relevant school-enterprise joint projects. The project results should be prioritized for use by enterprises. This would mobilize the enthusiasm of enterprises to cooperate in education.

6. Conclusion

The essence of the employment-oriented practical teaching reform in civil engineering and transportation majors is to align students’ professional literacy with job requirements, ultimately achieving a shift from skill training to holistic education. To accomplish this goal, schools should conduct sufficient market research to understand actual employment demands. Then, based on the professional teaching resources of the school, they should expand the boundaries of practical education. Simultaneously, schools need to promote further teaching reforms through diversified evaluation mechanisms, continuously providing impetus for educational transformation and upgrading.

Funding

Ministry of Education Supply and Demand Matching Employment Education Project, “Exploration and Practice of School-Enterprise Co-Education of Surveying and Mapping Professionals Under the Background of Industry-Education Integration” (Project No.: 2024010250340)

Disclosure statement

The authors declare no conflict of interest.

References

[1] Zhao R, Ran W, Lyu J, 2023, Exploration of Graduation Design Reform in Transportation and Civil Engineering Direction Under the Background of New Engineering—Taking Xinjiang University as an Example. Science and Technology Information, 21(2): 162–166.

[2] Wu B, Liu Y, 2022, Research on the Modern Apprenticeship Talent Training Mode of Vocational Civil Engineering Specialty. Journal of Liaoning Provincial College of Communications, 24(2): 64–67.

[3] Ai Q, 2024, Investigation and Analysis of Employment Status of Transportation Majors in Vocational Colleges Under the Background of Building a Powerful Transportation Country. Vocational Education, 23(5): 60–66.

[4] Zheng G, Liu X, Zhang Z, et al., 2025, Construction and Sharing Mechanism of Employment Practice Base for Smart Transportation Majors. Education and Teaching Forum, 2025(8): 20–23.

[5] Ai Q, 2024, Research on Monitoring and Optimization Countermeasures of Employment Quality of Graduates From Transportation Majors in Vocational Colleges Based on TMOF Theory. Vocational Education, 23(8): 17–23.

[6] Mo X, Zheng X, Li X, 2024, Exploring Innovation in Vocational College Rail Transit Professional Education Under the Guidance of Employment. Urban Mass Transit Research, 27(12): 23– 25.

[7] Ai Q, 2023, Construction and Evaluation of Employment Quality Monitoring System for Transportation Majors in Vocational Colleges Under the Background of High-Quality Development. Journal of Heilongjiang Vocational Institute of Eco-Engineering, 36(3): 105–111.

[8] Yang G, Li Y, 2025, Exploring the Path of Collaborative Education Through the Integration of Vocational Employment Education and Professional Education. Science and Technology Guide (Electronic Edition), 2025(1): 20–22.

[9] Wang Z, Nie Z, Liu Y, et al., 2024, Innovation and Practice of Classified Training Models for Urban Rail Transit Majors. Modern Business and Trade Industry, 45(8): 264–266.

[10] Xu C, Ruan H, Liu X, et al., 2024, Innovative Exploration of the Construction Mode of Employment Practice Training Base for Civil Engineering Majors Under the Background of Industry-Education Integration. Brick and Tile, 2024(5): 168–170.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Research on the Intelligent Design and Management of Buildings Based on the Internet of Things Engineering

Fan Wang*

Hainan Vocational University of Science and Technology, Haikou 571126, Hainan, China

**Author to whom correspondence should be addressed.*

Abstract: The Internet of Things (IoT) technology provides new impetus for the development of building intelligence. This research focuses on the intelligent design and management of buildings based on IoT engineering. It expounds on the system design principles such as sensor technology, communication network technology, and data storage and analysis, and analyzes the key points of design, including design requirement analysis, equipment layout, and system integration. Through specific cases, it demonstrates the application practice of the system in buildings, and presents the application effect of intelligent system management with multi-parameter values, providing theoretical and practical references for the development of building intelligence and helping to achieve efficient, energy-saving, and safe building operation.

Keywords: Internet of Things; Building intelligence; System design; Sensor technology; Data management

Online publication: June 30, 2025

1. Introduction

With the continuous progress of science and technology, the construction industry has ushered in new development opportunities. The traditional building management model has many problems, such as resource waste, low management efficiency, and difficulty in timely detection of potential safety hazards. It is increasingly difficult to meet the high requirements of modern society for building functions and performance [1]. IoT engineering, with its unique advantages, realizes the interconnection of devices and real-time data interaction through technologies such as sensors and communication networks, providing crucial support for the intelligent transformation of buildings [2]. Applying IoT engineering to the intelligent design and management of buildings can achieve precise monitoring and intelligent control of various aspects of buildings, such as internal equipment, environment, and energy consumption [3]. This can effectively improve building operation efficiency, reduce energy consumption costs, and enhance safety. Currently, building intelligence has become an important trend in the industry. In-depth research on the intelligent design and management of buildings based on IoT engineering is of great practical significance for promoting technological innovation in the construction industry and enhancing the comprehensive competitiveness of buildings.

2. System design principles

2.1. Sensor technology

Sensors, as key devices for obtaining information in IoT systems, play a sensing role in intelligent building systems. Different types of sensors can collect multi-dimensional information within buildings. Temperature sensors use thermosensitive elements to sense changes in environmental temperature and convert temperature signals into electrical signals for output, with an accuracy of up to ± 0.5°C, enabling real-time monitoring of indoor and outdoor temperature changes [4]. Humidity sensors utilize the capacitance characteristics of polymer films to measure air humidity, with a resolution of up to 1% RH, providing a data basis for indoor humidity control. Smoke sensors can respond rapidly when the smoke concentration reaches $0.01 mg/m^3$ through photoelectric or ion-sensing principles, achieving early-warning of fires [5]. Pressure sensors, based on the piezoresistive effect, can accurately measure information such as pipeline pressure and equipment stress, with an error of no more than ± 0.2% FS. Multiple sensors work together to construct a comprehensive information collection network, providing rich and accurate data for intelligent building systems.

2.2. Communication network technology

Communication network technology serves as a bridge for the interconnection of devices within buildings. Among wireless communication technologies, Bluetooth technology is suitable for short-distance data transmission between devices, such as the connection between smart locks and mobile phones. Its transmission distance is generally within 10 meters, and the transmission rate can reach 1Mbps [6]. ZigBee technology has the characteristics of low power consumption and self-networking, enabling wireless connection of multi-node devices within buildings. The communication distance ranges from 10 to 75 meters, and it supports multiple network topologies such as star-shaped and mesh–shaped [7]. Wi-Fi technology, with its high-speed transmission advantage, has a maximum transmission rate of up to 1Gbps and is widely used in high-speed data transmission scenarios within buildings, such as the real-time transmission of surveillance videos. In terms of wired communication technology, Ethernet uses the TCP/IP protocol, featuring stable transmission and high bandwidth [8]. It is often used for connecting core devices within buildings, with a transmission distance of up to 100 meters. Different communication technologies complement each other. According to the distribution and functional requirements of devices within buildings, a stable and efficient communication network is constructed to ensure reliable data transmission.

2.3. Data storage and analysis

Data storage and analysis are the core links for mining the value of building operation data. In terms of data storage, distributed storage technology is adopted, which distributes data across multiple nodes, improving the reliability and scalability of data storage. For example, the Ceph distributed storage system can dynamically expand the storage capacity according to the building scale and also has a data redundancy protection function to ensure data security. At the data analysis level, big data analysis technology is used to clean, transform, and analyze the collected massive data [9]. Cluster analysis can classify building energy consumption patterns, identify high energy consumption periods and areas. Correlation analysis can discover potential relationships between device operation parameters, such as the correlation between the operating temperature of air conditioners and the indoor population density. Machine learning algorithms can be used to predict device failures. By learning from the historical operation data of devices, a failure prediction model is established to identify device abnormalities in advance, providing a scientific basis for device maintenance.

3. Design of intelligent building management system

3.1. Design requirement analysis

The intelligent building management system needs to meet the requirements of the entire building life-cycle management. During the operation and maintenance stage, managers expect to have real-time access to device operation status, promptly detect potential failures, and arrange maintenance to reduce the risk of unplanned downtime [10]. In terms of energy conservation, through in-depth analysis of energy consumption data, the potential for energy savings is explored to achieve refined management of building energy and reduce operating costs. Different types of buildings have significant differences in requirements. Hospital buildings need to ensure the continuous power supply of medical equipment and environmental stability to ensure the normal operation of medical services. School buildings focus on the management of personnel evacuation safety and the control of environmental comfort in teaching areas. In addition, the system needs to have good compatibility, be able to connect devices of different brands and from different periods, and at the same time meet the requirements of data security and privacy protection to prevent data leakage and illegal access, building a solid security line for intelligent building management.

3.2. System architecture

The architecture of the intelligent building management system adopts a hierarchical design concept (refer to **Figure 1**). The perception layer consists of various sensors and intelligent terminals, responsible for collecting basic data such as device operation data, environmental parameters, and personnel activity information within the building, such as temperature-humidity sensors and current-voltage sensors. The network layer relies on wired and wireless communication networks to achieve efficient data transmission, accurately transmitting the data collected by the perception layer to the platform layer, and at the same time transmitting the control instructions of the platform layer to the execution devices [11]. The platform layer is the core of the system, undertaking data storage, processing, and analysis functions. It uses big data technology to clean and mine massive data, and through algorithm models, functions such as device failure prediction and energy consumption optimization are realized [12]. It also provides a unified management interface for managers to facilitate device management and strategy configuration. The application layer, based on the data and functions of the platform layer, develops diverse applications such as intelligent operation and maintenance, energy-saving management, and security monitoring to meet the needs of different users and achieve

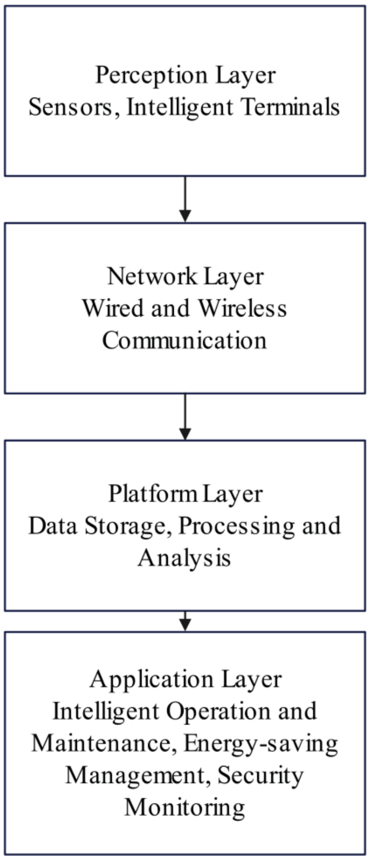


Figure 1. System architecture diagram

efficient operation and precise decision-making in intelligent building management.

4. Realization of intelligent building management functions

4.1. Communication control system integration

The integration of the communication control system realizes the interconnection of heterogeneous devices through standardized protocols and interfaces. Industrial-grade communication protocols, such as the MQTT protocol, are used to achieve lightweight communication between devices and the platform, reducing network load. The OPC UA protocol is used to achieve data semantic interoperability between devices of different manufacturers, eliminating information silos [13]. A distributed communication architecture is constructed, dividing the building into multiple communication sub-networks. Each sub-network realizes data aggregation and protocol conversion through gateways, enhancing the system's anti-interference ability and stability. At the control level, a hierarchical control mechanism is established. The underlying devices achieve autonomous logic control, the middle layer realizes device collaboration through regional controllers, and the top-level central control system conducts global strategy allocation to achieve the linkage control of lighting, air-conditioning, elevators, and other devices, improving building operation efficiency [14].

4.2. Real-time monitoring of buildings

The real-time monitoring system is based on the integration of multi-source data to construct a comprehensive monitoring system. It uses IoT sensors to collect device operation parameters, environmental indicators, and personnel activity information in real-time, and combines video surveillance and RFID positioning technology to achieve a three-dimensional perception of the building's physical space and personnel behavior. In terms of device monitoring, vibration sensors, infrared thermal imagers, and other devices are used to conduct non-invasive monitoring of key devices, obtaining data such as device vibration frequency and surface temperature, and the device health status is diagnosed in real-time through a state evaluation model. In environmental monitoring, air quality sensors, noise monitors, and other devices are deployed to draw a real-time distribution map of building environmental parameters, providing data support for environmental regulation [15]. Personnel monitoring uses access control systems and video analysis technology to keep track of personnel flow trajectories and gathering situations in real-time, ensuring the safe and orderly operation of the building.

4.3. Remote control of equipment

The remote control function of equipment is realized through a secure and reliable network channel and a permission management mechanism. Virtual Private Network (VPN) technology is used to establish an encrypted communication tunnel to ensure the secure transmission of remote control commands. A multi-role permission management system is designed to assign device operation permissions according to user responsibilities to prevent unauthorized operations. A cross-platform control application is developed, supporting access from multiple terminals such as PCs and mobile devices. Users can remotely start, stop, and adjust the operation parameters of equipment through a visual operation interface. In the remote control of air - conditioning systems, users can remotely set the operation mode and temperature value according to indoor and outdoor temperatures and population density. In elevator management, maintenance personnel can remotely view the elevator operation status, conduct fault diagnosis, and perform program upgrades, reducing on-site maintenance costs and enhancing equipment management flexibility [16].

4.4. Alarm and early-warning functions

The alarm and early-warning functions achieve intelligent early-warning through data mining and machine learning algorithms [17]. An abnormal data detection model is established, and threshold models and pattern recognition algorithms are trained based on historical data. When real-time data exceeds the normal range or an abnormal pattern appears, an immediate alarm is triggered, and relevant personnel are notified through multiple methods such as sound and light, text messages, and APP push notifications. Early-warning uses time-series analysis and fault prediction algorithms to analyze the trend of device operation data and predict the probability and time of device failures. For example, by analyzing the flow, pressure, and vibration data of water pumps, the LSTM neural network is used to predict the wear degree of water pump bearings, and maintenance plans are made in advance to eliminate potential failures, reduce equipment downtime losses, and ensure the stable operation of the building.

4.5. Data analysis and statistics

Data analysis and statistics focus on building operation data and use big data analysis technology to mine data value. A data warehouse is constructed to integrate multi-dimensional data, such as device operation, energy consumption, environment, and personnel. ETL technology is used for data cleaning, transformation, and loading. Data visualization tools are used to convert complex data into intuitive charts and dashboards, showing key indicators such as building energy consumption distribution, equipment utilization rate, and environmental quality changes. Algorithms such as cluster analysis and association rule mining are used to discover building operation laws and potential problems. For example, by analyzing the correlation between lighting energy consumption and personnel activity time, the lighting control strategy is optimized. By clustering the energy consumption patterns of different areas of the building, high energy consumption areas are identified, and energy-saving renovation plans are developed. At the same time, statistical reports and analysis reports are generated regularly to provide a scientific basis for building managers to promote the continuous improvement of intelligent building management levels.

5. Application case

5.1. Case background

A large-scale commercial complex is selected as a case. The complex has a total construction area of 250,000 square meters and consists of a shopping mall, Grade A office buildings, a five-star hotel, and an underground parking lot. The average daily footfall exceeds 50,000 people, and there are more than 2,000 pieces of equipment in the building, such as central air-conditioning systems, elevator group control systems, and intelligent lighting systems. Under the traditional management model, equipment operation and maintenance rely on manual inspections, resulting in serious energy waste and blind spots in safety monitoring. To solve these problems, the commercial complex introduced an intelligent building management system based on IoT engineering, aiming to create an efficient, energy-saving, and safe building operation environment and enhance the overall operation efficiency and user experience.

5.2. Application effect

Six months after the intelligent system was put into use, significant improvements were achieved in multiple key indicators of building operation. The specific data are shown in **Table 1**. From the data, it can be seen that the intelligent system has greatly reduced the daily total energy consumption through precise energy management strategies. The decrease in the energy consumption proportion of the air-conditioning system reflects the energy-saving advantages of intelligent control. The number of elevator failures has decreased significantly, improving equipment reliability and operational safety. The intelligent adjustment response time of the lighting system is controlled within 3 seconds, achieving timely and precise lighting control. The shortening of the response time for security incidents effectively guarantees the safety of personnel and property in the building. In addition, the improvement of indoor air quality and the increase in user satisfaction fully demonstrate the excellent results of the intelligent system in optimizing the user experience.

Table 1. Application effect of intelligent system management

Evaluation index	Before application	After application	Improvement rate
Daily total energy consumption (kWh)	12500	9200	26.4%
Energy consumption proportion of air-conditioning system (%)	45	38	15.6%
Intelligent adjustment response time of lighting system (s)	5	≤ 3	-
Average response time for security incidents (min)	15	5	66.7%
Number of elevator failures (times/month)	8	2	75%

6. Conclusion

The intelligent design and management of buildings based on IoT engineering realize the intelligent operation and efficient management of buildings through advanced sensor technology, communication network technology, and data processing technology. This research starts from the system design principles, elaborates on the key points of intelligent building design, and verifies its application effect through practical cases. The research shows that this technology can effectively improve the energy utilization efficiency, management level, and safety of buildings.

Disclosure statement

The author declares no conflict of interest.

References

[1] Sanchez GA, Vallerotto G, Askins S, et al., 2025, A Smart Semi-Translucent Building-Integrated PV Module Based on Integrated-Tracking Micro-Concentration Providing High Power Density and Active Daylight Management. Solar Energy Materials and Solar Cells, 287: 113246.

[2] Liu Y, Zhou S, Cao S, 2025, Optimal Management of Smart Grid Rental and Electric Vehicles for Remote Energy Sharing Between Distinct-Scale Buildings With Novel Business Model Development. Sustainable Cities and Society, 124: 106305.

[3] Mei Z, Ding Y, Wang M, et al., 2025, A Colorful Electrochromic Infrared Emissivity Regulator for All-Season Intelligent Thermal Management in Buildings. Advanced Materials, 2025: e2420578.

[4] Rojek I, Mikolajewski D, Mrozinski A, et al., 2025, Internet of Things Applications for Energy Management in Buildings Using Artificial Intelligence—A Case Study. Energies, 18(7): 1706.

[5] Kim J, Park S, Moukhliss S, et al., 2025, Perceptions of Artificial Intelligence (AI) in the Construction Industry Among Undergraduate Construction Management Students: Case Study—A Study of Future Leaders. Buildings, 15(7): 1095.

[6] Shen R, Zheng R, Yang D, et al., 2025, Towards Intelligent Management of Regional Building Energy Systems: A Framework Combined With Deep Reinforcement Learning for Hybrid Energy Storage. Energy Conversion and Management, 329: 119656.

[7] Briones GA, Sanchez PJ, Vale Z, et al., 2025, Evolution of Building Energy Management Systems for Greater Sustainability Through Explainable Artificial Intelligence Models. Engineering Applications of Artificial Intelligence, 147: 110324.

[8] Javaherikhah A, Sarvari H, 2025, Implementing Building Information Modeling to Enhance Smart Airport Facility Management: An AHP–SWOT Approach. CivilEng, 6(1): 15.

[9] Wang J, Du J, Luo D, et al., 2025, Retraction Notice to 'An Optimal Multi-Objective Demand Side Management of a Smart Microgrid Consists of Various Building Loads, Considering Relativity Index and Uncertainty'. Journal of Building Engineering, 101: 111829.

[10] Cascone S, Parisi G, Caponetto R, 2024, BIM-Based Strategies for the Revitalization and Automated Management of Buildings: A Case Study. Sustainability, 16(16): 6720.

[11] Franco A, Crisostomi E, Dalmiani S, et al., 2024, Synergy in Action: Integrating Environmental Monitoring, Energy Efficiency, and IoT for Safer Shared Buildings. Buildings, 14(4): 1077.

[12] Arka G, Jemal A, Morshed C, 2024, Redefining the Construction Managerial Landscape to Facilitate Industry 4.0 Implementation: Scientometric Mapping of Research Frontiers. Construction Innovation, 24(3): 657–683.

[13] Jelle V, Emiel D, Pieter B, et al., 2023, Real-Time Estimation and Monitoring of COVID-19 Aerosol Transmission Risk in Office Buildings. Sensors, 23(5): 2459.

[14] Gnecco VM, Vittori F, Pisello AL, 2023, Digital Twins for Decoding Human-Building Interaction in Multi-Domain Test-Rooms for Environmental Comfort and Energy Saving via Graph Representation. Energy and Buildings, 279: 1–32.

[15] Muhammad U, Salah KAY, Karam JAM, et al., 2022, A Low-Cost IoT-Based Buildings Management System (BMS) Using Arduino Mega 2560 and Raspberry Pi 4 for Smart Monitoring and Automation. International Journal of Electrical and Computer Engineering Systems, 13(3): 219–236.

[16] Baradaran M, Khosravi RM, Akbarzadeh O, 2021, IoT Solutions for Smart Management of Hospital Buildings: A General Review Towards COVID-19, Future Pandemics, and Infectious Diseases. Current Signal Transduction Therapy, 16(3): 240–246.

[17] Yu M, Menglu Y, Hao J, 2020, Application of Computer Internet of Things Technology in Building Intelligent System. Journal of Physics: Conference Series, 1648(2): 022184

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Renewal Design of an Urban Heritage Park: The Case of King Yu's Terrace Park

Qianqian Zhang*, Ziyuan He, Kaiwen Sun

Academy of Arts and Media, Environmental Design, Shangqiu University Applied Science and Technology College, Kaifeng 475000, China

**Author to whom correspondence should be addressed.*

Abstract: With the increasing awareness of heritage city protection around the world, relevant laws and regulations are constantly improving, and the methods and approaches for protection are gradually enriching [1]. Heritage protection work has made significant progress. In recent years, heritage parks have become an effective model for balancing urban construction and heritage protection, not only for the effective protection of the site itself and its environment, but also for the use of the site and its cultural heritage [2]. This article takes King Yu's Terrace Park as an example for research. As an ancient capital of eight dynasties, Kaifeng in Henan Province has many historical relics, one of which is King Yu's Terrace Park. The overall renewal planning and design of the park focuses on the protection of ancient buildings, ecological landscape design, and cultural display [3]. A complete set of planning and design strategies is summarized to provide reference for the future renewal and renovation of King Yu's Terrace Park.

Keywords: Heritage park; Protection of ancient architecture; Ecological landscape design; Cultural display.

Online publication: June 30, 2025

1. Project overview

The project is located in Kaifeng City, Henan Province, China, in the central region of China, the Eastern part of Henan Province, and the hinterland of the Central Plains. It is one of the central cities in the core area of the Central Plains City Cluster of China, a cultural and tourist city, as approved by the State Council. It has a total area of 6266 square kilometers and a resident population of 4824016 (**Figure 1**).

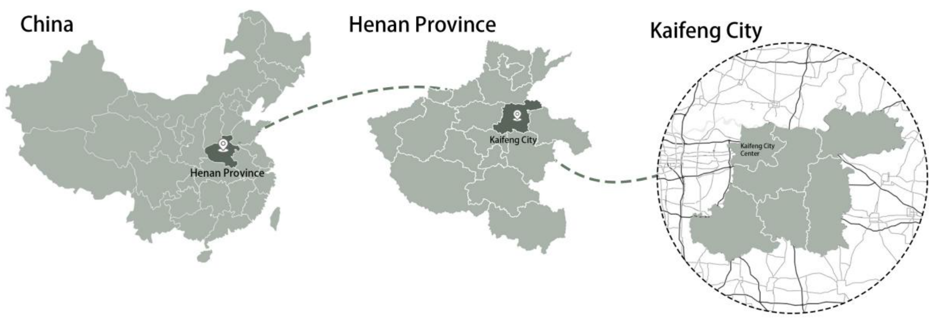


Figure 1. Location analysis diagram

2. Site analysis

2.1. Macro analysis

2.1.1. Project location analysis

King Yu's Terrace Park is located in China's Henan Province Kaifeng City. The Southeastern corner of the city is dominated by the surviving Yuwangtai. The park is named after the existing King Yu's Terrace. King Yu's Terrace Park has a long history and a rich cultural heritage. It was opened as a park in 1955 and has experienced a history of 2,500 years since then. The park covers an area of 26.1 hectares (**Figure 2**).

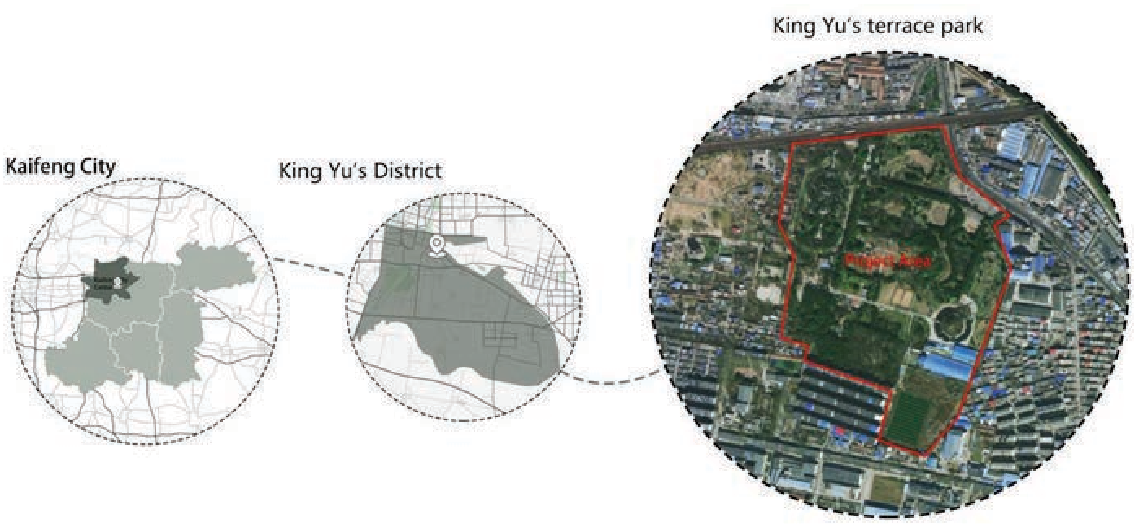


Figure 2. Park location diagram

2.1.2. Conservation Planning of the ancient city layout analysis

According to the Kaifeng Old Town Pattern Conservation Plan, King Yu's Terrace Park is an important historical and cultural conservation area, undertaking the role of heritage conservation and spreading historical culture (**Figure 3**). The protection and display of the existing ancient buildings within the park should be enhanced so that more people can understand the history and culture behind them.

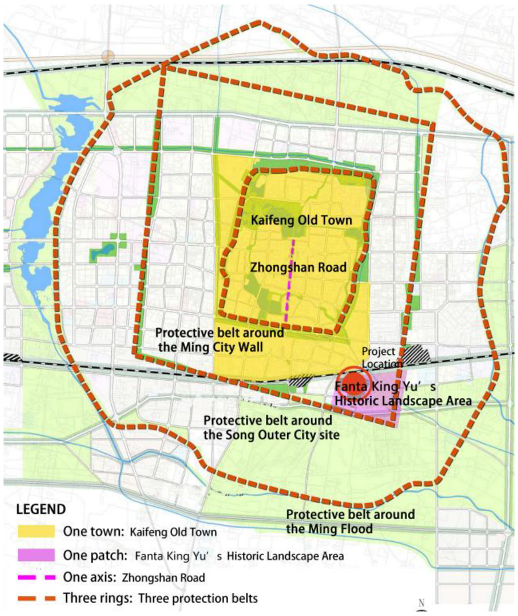


Figure 3. Kaifeng Conservation Planning of the ancient city layout diagram

2.1.3. Current situation of tourism resources analysis

Kaifeng has 8 national 5A and 4A tourist attractions and 19 national key cultural relics protection units. China Kaifeng Qingming Cultural Festival, the China Kaifeng Chrysanthemum Cultural Festival attract many tourists from home and abroad (**Figure 4**). Most of the heritage parks and sites are concentrated in the city centre. In the King Yu's Terrace District, there is only one King Yu's Terrace Park.

Figure 4. Kaifeng, current situation of tourism resources diagram

2.1.4. Historical and cultural analysis

King Yu's Terrace Park has a long history and a rich cultural heritage. It was opened as a park in 1955 and has experienced a history of 2,500 years since then, and is one of the key cultural heritage protection units (**Figure 5**). The main attractions include the Ancient Blowing Platform, the Imperial Book Building, the Qianlong Imperial Tablet Pavilion, the Three Sages Ancestral Hall, the Yu Wang Hall and the Water Virtue Ancestral Hall. In addition to the cultural relics, the park also has the Xinhai Revolution Martyrs' Memorial Garden, Peony Garden, Cherry Garden, Fangchun Garden, and other sightseeing spots, which are national A-class tourist attractions.

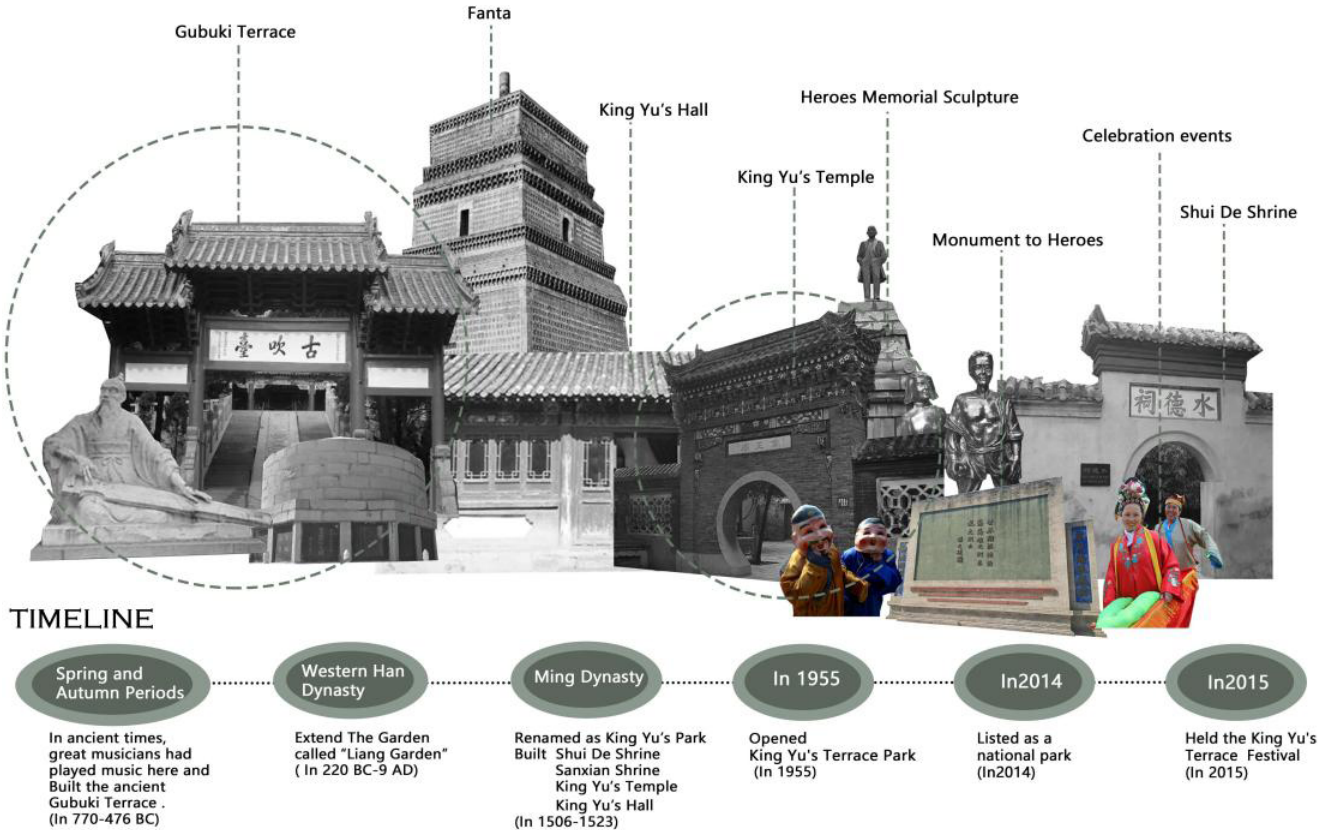


Figure 5. King Yu's Terrace Park historical and cultural diagram

2.2. Meso-analysis

2.2.1. Surrounding traffic analysis

The area around King Yu's Terrace Park is well served by transport facilities for easy commuting. It is bordered by the train tracks to the North, Fanta I Street to the West and King Yu's Terrace Road to the East. The planned road network is well-connected and residents can reach the park entrance from a number of roads. There are a number of bus stops within 500 metres of the site, making it easy for residents to access the park (**Figure 6**).

2.2.2. Surrounding green space analysis

In the vicinity of King Yu's Terrace Park, there is only one Fanta Park within a distance of 500 meters and a series of parks around the city wall within a distance of 1000-1500 meters (**Figure 7**). Therefore, it is clear that there is a lack of large parks for leisure, fitness, and recreation for the surrounding residents, and that King Yu's Terrace Park, as the green centre of the King Yu's Terrace district, should provide a better space for green services.

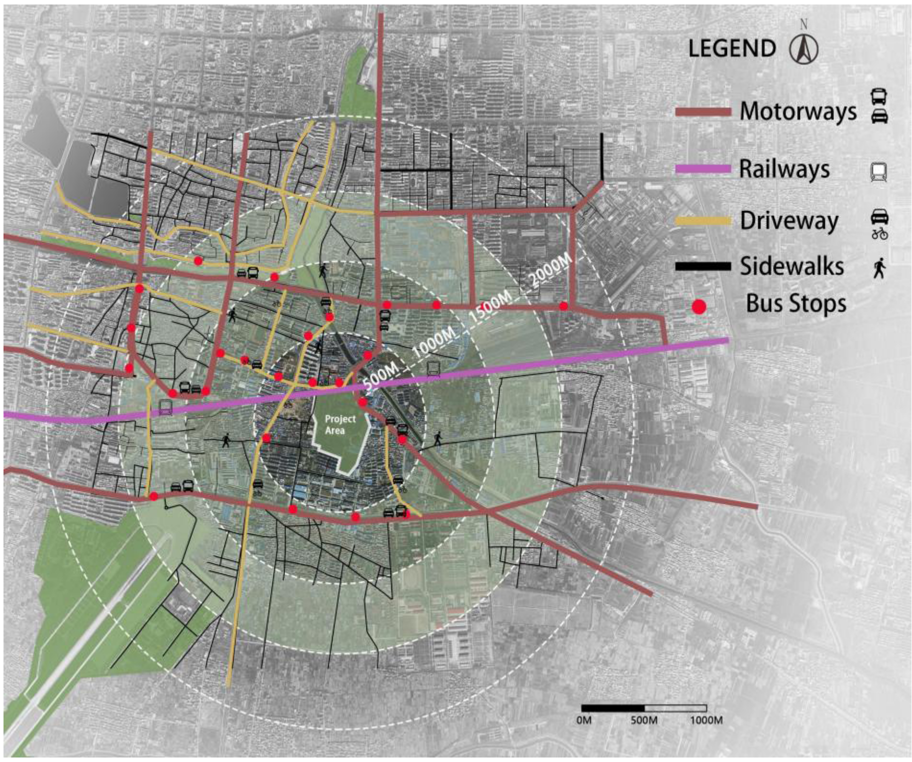


Figure 6. King Yu's Terrace Park surrounding traffic diagram

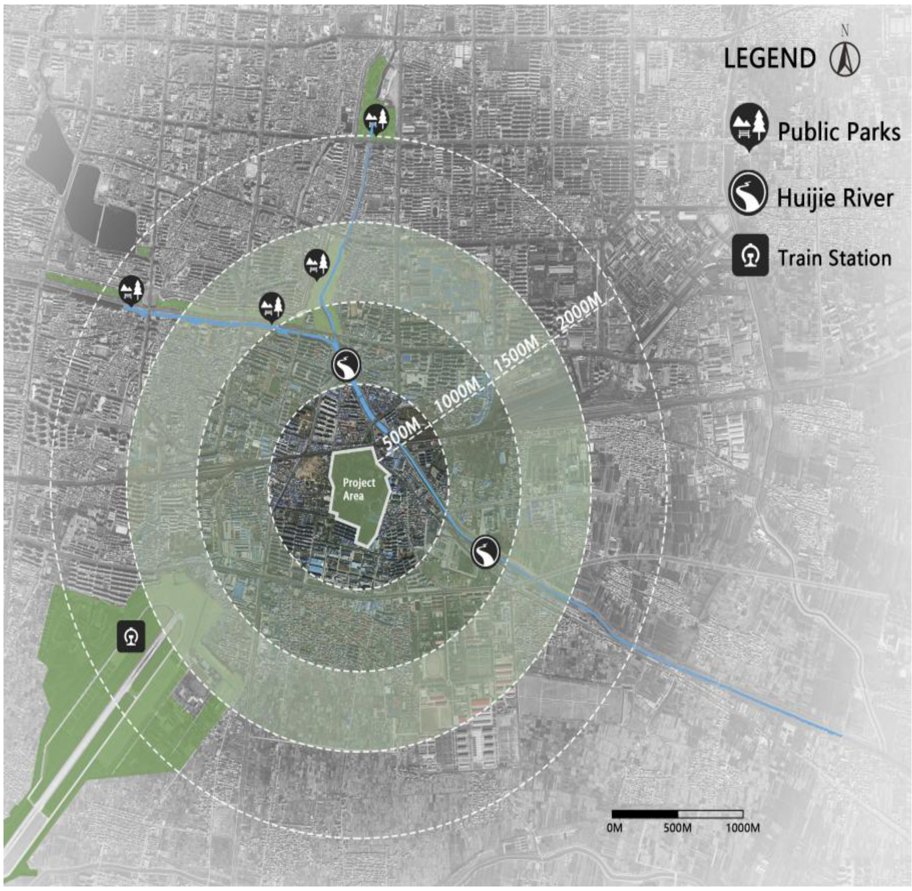


Figure 7. King Yu's Terrace Park surrounding green space diagram

2.2.3. Surrounding site land use analysis

The surrounding area is predominantly residential, with some commercial activity present. Around the site, the mixed buildings are mostly low-rise, with the residential buildings being high-rise. To the West of this park is a small park, famous for the Fanta, one of the oldest surviving Buddhist buildings in Kaifeng. The park is enclosed on all sides, with a fence as a boundary line. Only two entrances can be accessed, the main entrance area with a large parking area and a secondary entrance connected to the Prosperity Tower Park (**Figure 8**).

Figure 8. King Yu's Terrace Park surrounding green space diagram

2.3. Micro-analysis

2.3.1. Summary of current issues

(1) Current state of the building: The old building is well preserved but lacks display design. The other service buildings are in a state of disrepair, affecting their use.

(2) Infrastructure: There is very little infrastructure within the park, with only a small number of facilities for children's activities, sports activities, and benches. Most of the infrastructure is in a state of disrepair.

(3) Paving: The paving materials for roads are mainly brick, gravel, asphalt, concrete, and rubber. The quality of the paving materials has also deteriorated due to prolonged use. Also, due to the lack of overall planning and design of the roads, there is also a part of the pavement where people walk out on their own.

(4) Plants: As this is a historical park, most of the plants inside the park are very tall, but a lack of maintenance and management means that many of them grow wild. There are also a few plants in a poor state of growth.

(5) Water resources: Most of the water resources within the park have dried up due to a lack of management over a long period of time. Only the area of the water park has a small amount of existing water. The dried-up rivers should affect the aesthetics of the landscape (**Figure 9**).

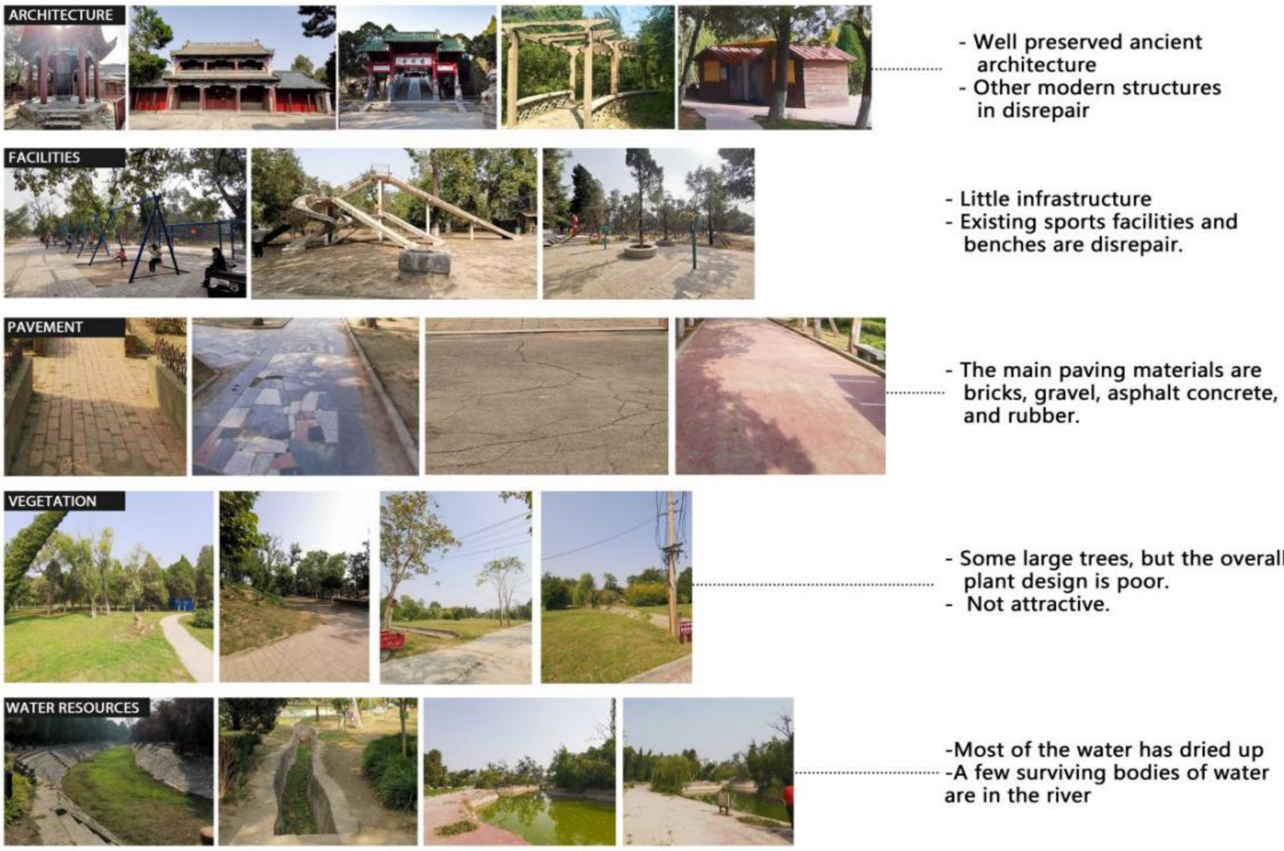


Figure 9. Current issues diagram

3. Design goals and strategies

3.1. Design goals

Based on the above analysis and discussion, it was determined that King Yu's Terrace Park would aim at ancient preservation, cultural display, and ecological landscape design, featuring the promotion of 'Song' culture and creating a heritage park that effectively conveys historical and cultural information (**Figure 10**) [4].

Figure 10. Design goal diagram

3.2. Design strategies

According to the analysis of the current situation, the design strategy for the renewal of King Yu's Terrace Park focuses on three directions. Ancient architecture protection, ecological landscape design, and cultural display (**Figure 11**)[5].

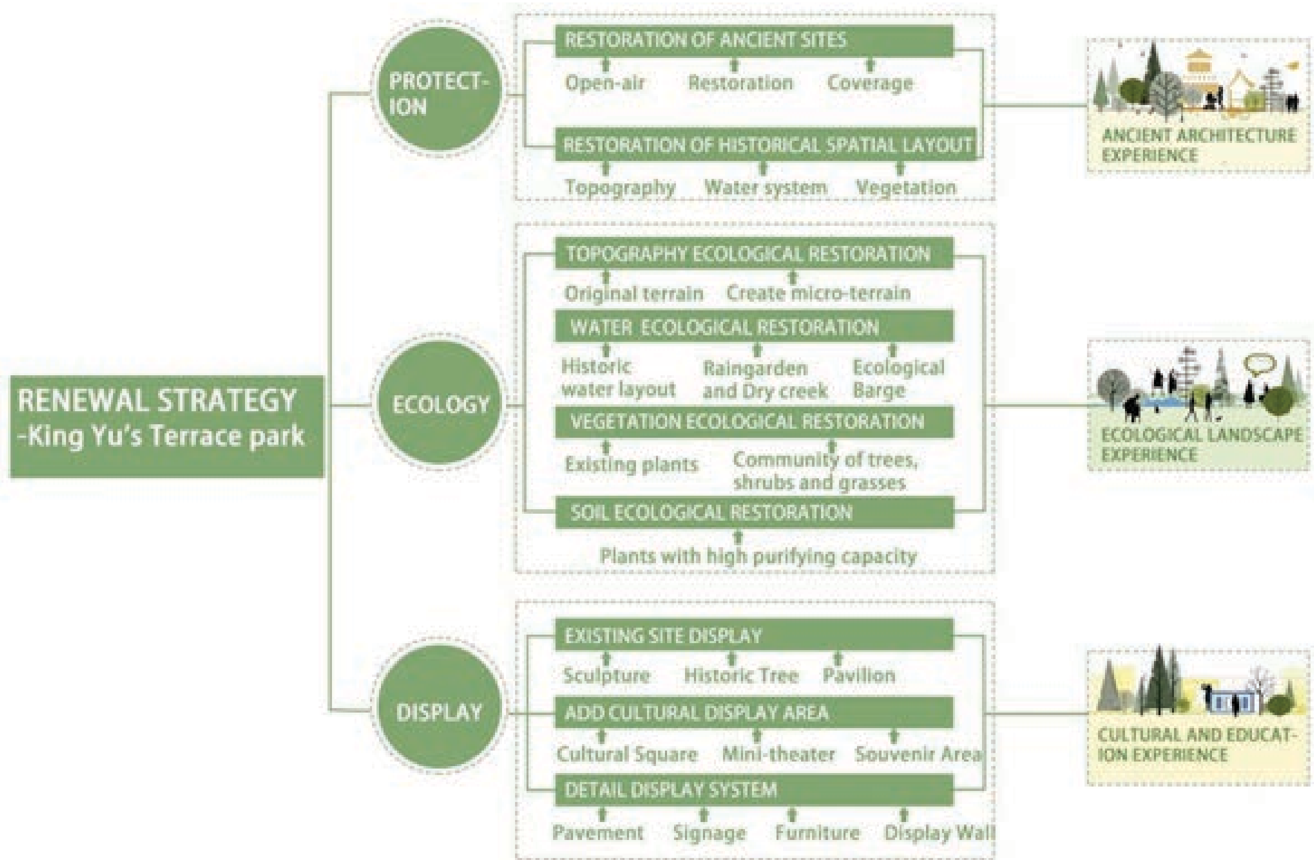


Figure 11. Design strategy diagram

3.2.1. Design strategy of protection

In terms of protection, the restoration of the ancient architectural body and the restoration of the historical spatial layout are used (**Figure 12**). Ancient architecture protection is the way to present the original appearance of the site, its own value and excavated artifacts to the public. For sites with overlapping remains from different periods, the focus should be highlighted and the logical hierarchy in time and space should be handled [6].

The current site landscape protection measures and display methods do not have a unified standard, as summarized through relevant information. The main object of this study can be divided into open-air protection display, restoration and protection exhibition and site reconstruction display three ways [7]. Historical spatial layout restoration appropriately strengthens the restoration of topography, water system, plants and ancient site boundaries to strengthen the original pattern of the park display. Greening, structures, roads, and other means are used to strengthen the existing archaeological zoning boundaries and improve boundary recognition. High platforms, landscape pillars, and landscape frames are set up to guide the control of angular views, provide multiple perspectives of top, flat, and elevated views, and create a variety of landscapes, such as frames and pairs of views, to strengthen the viewer's perception of the site [8].

Figure 12. Design strategy of protection diagram

3.2.2. Design strategy of ecological landscape design

In terms of ecological landscape design, the main focus is on the ecological restoration of the site's internal topography, water, plants, and soil (**Figure 13**).

The topography design of the site park is to preserve the original topography of the park, while making full use of the current topography to create micro-topography, increase the topographic changes inside the park, and enrich the sense of different spatial experiences [9]. The ecological nature of the site is improved through planting design and terrain design.

The water design restores the original water pattern of the park, and according to the current conditions of the park, a wetland is designed in the high topography area of the park and a dry creek is designed in the low topography area to establish the first ecological barrier for the internal environment of the site [10]. In addition, permeable pavement is used for roads, squares, parking lots, etc., and grass planting ditches are used around the perimeter to effectively slow down surface runoff and play a good filtering role for rainwater, and the construction and maintenance costs are low, which also follows the principle of economical and applicable landscape ecological restoration construction [11].

The planting design should take the protection and display of the site as the core, not to destroy the original vegetation, and to preserve the old trees and well-grown plants in the current situation inside the site. At the same time, some native plants and exotic plants are added to enrich the plant species, create a beautiful plant landscape and a good combination of plant community relationship of trees, shrubs, and grasses.

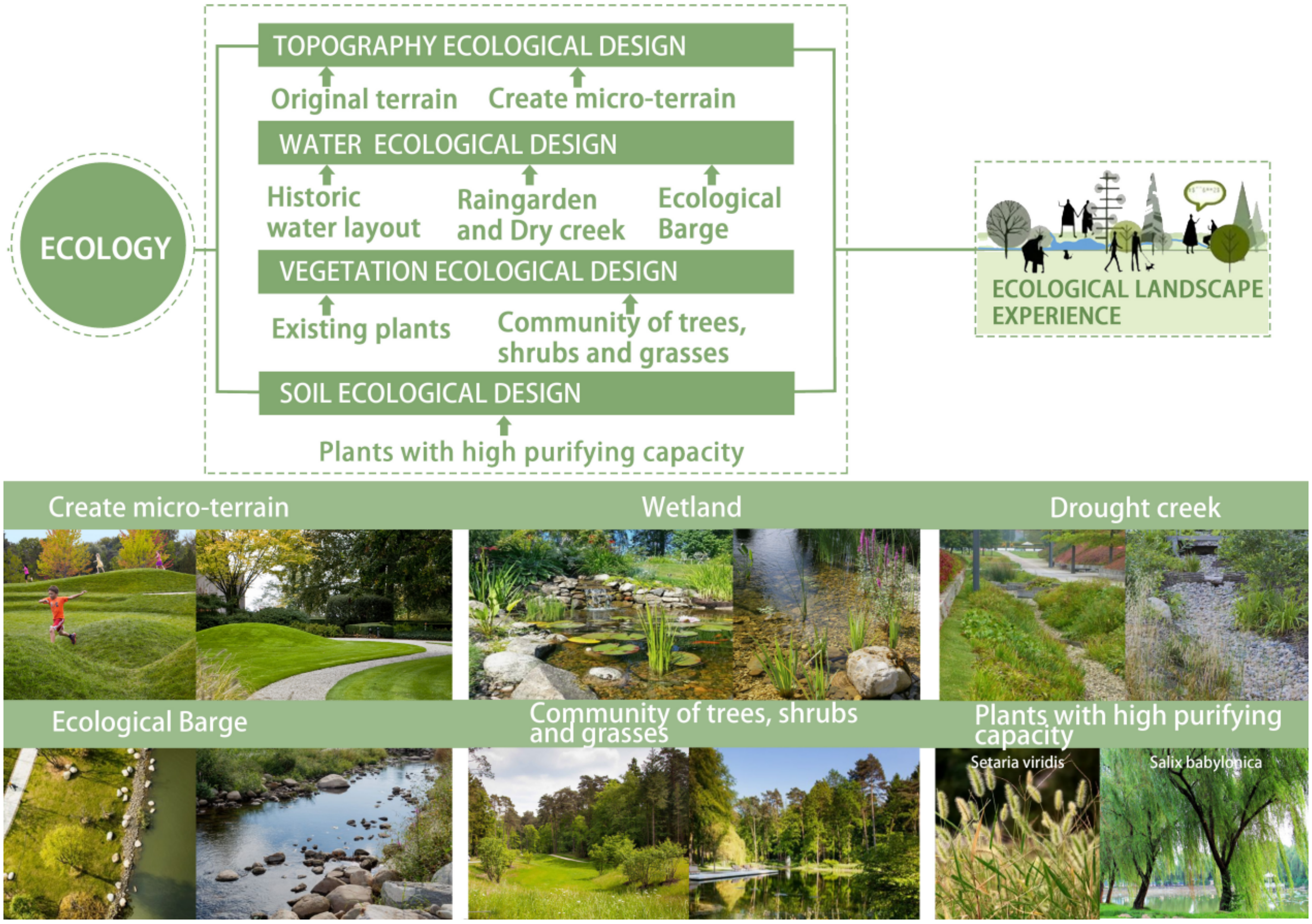


Figure 13. Design strategy of ecological landscape design diagram

3.2.3. Design strategy of cultural display

In terms of cultural display, the current site display is adopted, increasing the cultural display function area and detail display (**Figure 14**). The current site display is a cultural display through the design of cultural sculpture, ancient trees, and antique buildings. The cultural display function area can be designed for handicraft experience, a small theater, and a souvenir display area [12]. Detail display design refers to the selection of paving materials, signage design, furniture design, and the design of cultural display landscape walls [13]. In the design of historical and cultural park, this details design has a good landscape expression effect and can also play the role of cultural communication.

Figure 14. Design strategy of cultural display diagram

4. Conclusions

In heritage parks, priority should be given to heritage protection, and then, combined with the historical and cultural characteristics of the site, ecological design methods should be adopted to form a unique public green activity space [14]. This article analyzes the current situation of King Yu's Terrace Park from different levels of macro, meso, and micro, and proposes planning and design strategies for the park's renewal and renovation from three perspectives: ancient building protection, ecological landscape design, and cultural display [14]. This provides reference significance for the future renewal and renovation of King Yu's Terrace Park.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Li X, Ma S, 2013, Exploration on the Construction of Yinxu Archaeological Site Park and Economic Development in the Protected Area. Journal of Anyang Engineering College, 2013(6): 86–88.

[2] Jiang M, 2015, Synergistic Study on the Conservation of Large Heritage Sites and Urban Development, thesis,

Northwestern University.

[3] Bastian O, Walz U, Decker A, 2013, Historical Landscape Elements: Part of our Cultural Heritage - A Methodological Study from Saxony. The Carpathians: Integrating Nature and Society Towards Sustainability: 441–459.

[4] Clark K, 2019, Power of Place - Heritage Policy at the Start of the New Millennium. The Historic Environment Policy and Practice, 10(3–4): 255–281.

[5] Sirisrisak T, 2009, Conservation of Bangkok Old Town. Habitat International, 33(4): 405–411. Preservation Education and Research, 33(4): 405–411.

[6] Way T, Callcott S, 2009, Expanding Histories / Expanding Preservation: The Wild Garden as Designed Landscape. Historic Preservation, 2: 53–64, 93.

[7] Xie J, 2021, Planning and Design of Ming Great Wall Heritage Park Based on Living Display, thesis, Beijing Forestry University.

[8] Wang X, 2021, Research on the Planning and Design of Nanchang Han Dynasty Haiyang Hou Site Park Featuring Cultural Experience, thesis, Zhejiang Agriculture and Forestry University.

[9] Tan T, 2017, Research on the Design of Archaeological Site Park Based on Conservation and Display, thesis, Soochow University.

[10] Zhang S, 2022, Research on Landscape Ecological Restoration Design of Industrial Manufacturing Waste Sites, thesis, Xi'an University of Architecture and Technology.

[11] Zhou M, 2021, Research on the Planning and Design of Heritage Parks Based on Conservation and Display, thesis, Beijing Forestry University.

[12] Ye L, Lin H, Chen X, 2024, Narrative Design of Red Cultural Heritage Landscape in Jiangxi Province—Take Fang Zhimin Martyrs' Memorial Park as an Example. Journal of Research in Science and Engineering, 5(5): 21–28.

[13] Hung C, 2023, A Study on the Impact of "Experience Design" of Art and Culture Exhibition on "Brand Loyalty" of Cultural Park Exhibition in the Cultural Heritage Park of the Ministry of Culture as Case Study. Journal of the Science of Design, 7(2): 211–220.

[14] Hyun C, Kim HS, 2011, A Design of Smart Contents Platform for Memory Heritage: Story Theme Park of Story. ugyo.net. Korean Contents Association ICCC Journal, 11(2): 23–24.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Numerical Simulation of M-Shaped Multi-Row Pile-Supported Foundation Pit Excavation Based on ABAQUS

Meng Chen[1], Chuanteng Huang[1]*, Shuang Pu[1], Jilun Cai[1], Zuocai Li[2], Yufu Huang[1]

[1]School of Engineering, Zunyi Normal University, Zunyi, China
[2]China Railway 22nd Bureau Group Electrification Engineering Co., Ltd., Beijing 100043, China

Author to whom correspondence should be addressed.

Abstract: The M-shaped multi-row pile foundation retaining structure represents an enhanced version of conventional multi-row anti-sliding support systems. To date, the implementation of M-shaped pile configurations in foundation pit excavations has not been extensively investigated, with particularly scant research focusing on their load-bearing mechanisms and stress redistribution characteristics. Furthermore, numerical modeling methodologies for such geometrically optimized pile networks remain underdeveloped compared to practical engineering applications, creating a notable research-practice gap in geotechnical engineering. A comparative finite element analysis was systematically conducted using ABAQUS software to establish three distinct excavation support configurations: single-row cantilever retaining structures, three-row cantilever configurations, and M-shaped multi-row pile foundation systems. Subsequent numerical simulations enabled quantitative comparisons of critical performance indicators, including pile stress distribution patterns, lateral displacement profiles, and bending moment diagrams across different structural typologies. The parametric investigation revealed characteristic mechanical responses associated with each configuration, establishing corresponding mechanical principles governing the interaction between pile topology and soil-structure behavior towers. The findings of this study provide critical references for the design optimization of M-shaped multi-row pile foundation retaining systems.

Keywords: M-shaped multi-row piles; Foundation pit excavation; Numerical simulation; ABAQUS

Online publication: June 30, 2025

1. Introduction

The current urbanization rate exceeding 65% in China has escalated technical challenges in deep excavation engineering and geohazard mitigation under complex construction site conditions and geological constraints. Conventional retaining structures enhance stability through increased pile cross-sectional dimensions, yet incur construction complexities and economic inefficiencies. H-shaped and M-shaped multi-row pile configurations have emerged as a research focus due to their cost-effectiveness and structural efficiency, while M-shaped variants particularly lack sufficient theoretical substantiation and demonstrate limited field implementation maturity.

Cai demonstrated the feasibility of single-row bored pile retaining systems through ultra-deep foundation pit engineering applications [1]. Xiong identified two distinct deformation patterns (“V”-type and “W”-type configurations) in H-shaped retaining structures [2]. Li established laboratory-scale H-pile models providing theoretical foundations for optimizing cantilever length and connecting beam dimensions [3].Li developed a three-row anti-slide pile finite element model, proposing optimal pile spacing values at rock-debris interfaces [4]. Zou employed FLAC3D simulations to analyze wedge-shaped pile behavior, revealing significant regulatory effects of wedge angles on stress distribution [5]. Zhang established H-shaped pile-soil interaction models using ABAQUS, determining 2.5 times pile diameter as the optimum inter-row spacing [6]. Wu simulated pile position impacts on slope stability, identifying 3m from slope crest as the optimal layout position [7]. Zhan conducted PLAXIS3D comparisons between parallel and staggered pile arrangements, confirming that rear-row piles bear predominant load-bearing functions [8].

Current numerical modeling practices for M-shaped multi-row pile foundations predominantly focus on individual configuration analyses, with existing studies conspicuously lacking comparative investigations against conventional pile typologies. Current simulation methodologies exhibit limitations in pile arrangement diversity, with insufficient parametric investigations addressing stiffness variations in pile elements and connecting beams. Furthermore, numerical simulation studies focusing on M-shaped multi-row pile foundation retaining systems under deep excavation scenarios demonstrate notable scarcity, while the mechanical implications of critical design parameters (e.g., pile spacing ratios and flexural rigidity coefficients) on structural stress redistribution remain insufficiently quantified.

This study systematically develops finite element models in ABAQUS to comparatively analyze three excavation support systems: single-row cantilever retaining structures, three-row cantilever configurations, and M-shaped multi-row pile foundation systems. Quantitative comparisons reveal distinct patterns in pile stress distribution, lateral displacement characteristics, and bending moment diagram configurations across different structural typologies. The established mechanical principles governing load-transfer mechanisms provide practical references for geotechnical engineering design practices.

2. Numerical simulation of foundation pit excavation based on ABAQUS

2.1. Engineering problem description

As illustrated in **Figure 1**, the foundation pit exhibits the excavation width of b × S = 2m × 20m, and the depth of $H_1 = 10m$. Three distinct retaining systems are implemented: Single-row cantilever retaining structure, Three-row cantilever retaining structure, and M-shaped retaining system.

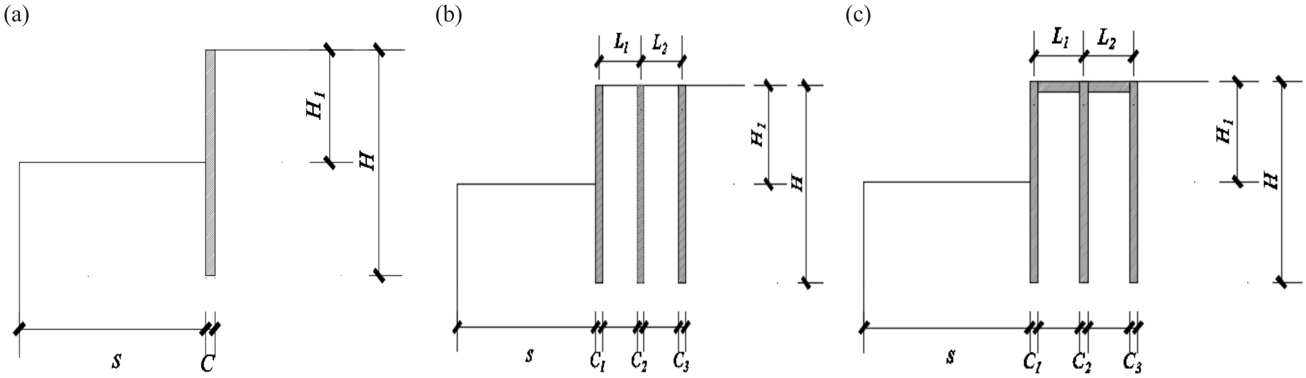


Figure 1. Diagrams of various retaining structures; (a) Cantilever retaining structure; (b) Three-row cantilever retaining structure; (c) M-shaped retaining system

All retaining piles exhibit uniform dimensions: width $C = C_1 = C_2 = C_3 = 1m$ and embedded length $H = 20m$. For multi-row configurations: Center-to-center pile spacing: $L_1 = L_2 = L_3 = 6m$; M-shaped connecting beam: Thickness $T = 1m$. Material properties are defined as: Pile elastic modulus: $E_0 = 28000000k$Pa, Soil elastic modulus: $E = 66000k$Pa, Lateral earth pressure coefficient: $K_h = 2$. The foundation pit parameters are detailed in **Table 1**, while the soil and pile properties are tabulated in **Table 2**. All connecting beam parameters exhibit identical values to those of the piles.

Table 1. Foundation pit parameters

Excavation depth H_1 (m)	Pile thickness C (m)	Pile length H (m)	Pile spacing L_0 (m)	Coupling beam thickness T (m)
10	1	20	6	1

Table 2. Pile-soil physical parameters

	Friction angle φ/(°)	Dilation angle φ'/(°)	Cohesion c/kPa	Unit weight γ/(kN·m-3)	Poisson's ratio v	Elastic modulus E (kPa)
Soil	30	0	0	20	0.2	66000
Pile	-	-	-	-	0.15	28000000

2.2. Numerical simulation of foundation pit excavation

Given the consistent modeling procedures across the three configurations, the single-row cantilever retaining structure was selected to establish the procedural framework for numerical simulation of foundation pit excavation, as detailed below:

2.2.1. Model construction and partitioning

Two-dimensional components comprising a soil domain (100 × 100 square) and pile elements (1 × 120 rectangular) were created. The geometry was partitioned to demarcate pile installation zones and excavation regions, followed by the establishment of contact interface sets.

2.2.2. Material property assignment

The Mohr-Coulomb constitutive model was assigned to the soil, while an elastic model was adopted for the piles.

Material parameters were defined as follows:

(1) Soil properties: Elastic modulus E = 66kPa, Poisson's ratio $\mu = 0.2$, Friction angle $\phi = 30$, Cohesion c = 0.1kPa

(2) Pile properties: Elastic modulus E = 28MPa, Poisson's ratio $\mu = 0.15$

Section properties were subsequently assigned to the respective components.

2.2.3. Assembly and contact definition

Components were assembled and spatially aligned. Pile-soil contact pairs were defined with tangential behaviour governed by a penalty friction formulation (coefficient = 0.577) and normal behaviour enforcing hard contact constraints. Specific contact pairs were systematically deactivated during excavation phases to simulate progressive soil removal.

2.2.4. Analysis step configuration

Two analysis steps were established:

(1) Initial geostatic step (geo): For achieving geostatic equilibrium under gravitational loading.

(2) Excavation step (Remove): Employing asymmetric matrix storage to enhance computational convergence during contact evolution, with an increment size range of 0.1–0.2.

2.2.5. Boundary conditions and loading

Horizontal displacement constraints were imposed on the model sides, while full fixity was enforced at the base. A gravitational body force of -20 (unitless normalized acceleration) was applied to replicate geostatic loading. The initial stress field was initialized through depth-dependent stress gradients, accounting for lithostatic pressure distribution.

2.2.6. Mesh generation

A structured mesh comprising 20×3 incompatible modes elements was implemented. The soil domain was discretized using quadrilateral plane strain elements, with mesh density controlled through local seeding parameters (minimum element size: 0.5 units; maximum element size: 10 units).

2.2.7. Excavation simulation

Material removal in designated zones was executed via the Model Change feature, with computational tasks submitted to simulate the staged excavation process. Critical operational aspects encompassed dynamic management of contact pairs and enforcement of mesh convergence criteria.

3. Comparative analysis of different pile-type retaining structures

3.1. Numerical case design

Preliminary finite element comparative analysis of single-row, Three-row cantilever retaining structures and M-shaped pile foundation retaining structures via numerical cases are summarized in **Table 3**.

Table 3. Numerical case parameters

	Pile thickness C(m)	**Pile length H(m)**	**Pile spacing L_0(m)**	**Coupling beam thickness T(m)**	**Elastic modulus of pile body E_0(kPa)**	**Elastic modulus of connecting beam E(kPa)**
Cantilever retaining structure	1	20	-	-	28000000	-
Three-row cantilever retaining structure	1	20	6	-	28000000	-
M-Shaped retaining system	1	20	6	1	28000000	28000000

3.2. Analysis of results

Through finite element analysis, horizontal displacement contour maps of the retaining structures and soil mass were obtained (**Figure 2**) (Note: Positive values indicate rightward displacement, and negative values indicate leftward displacement).

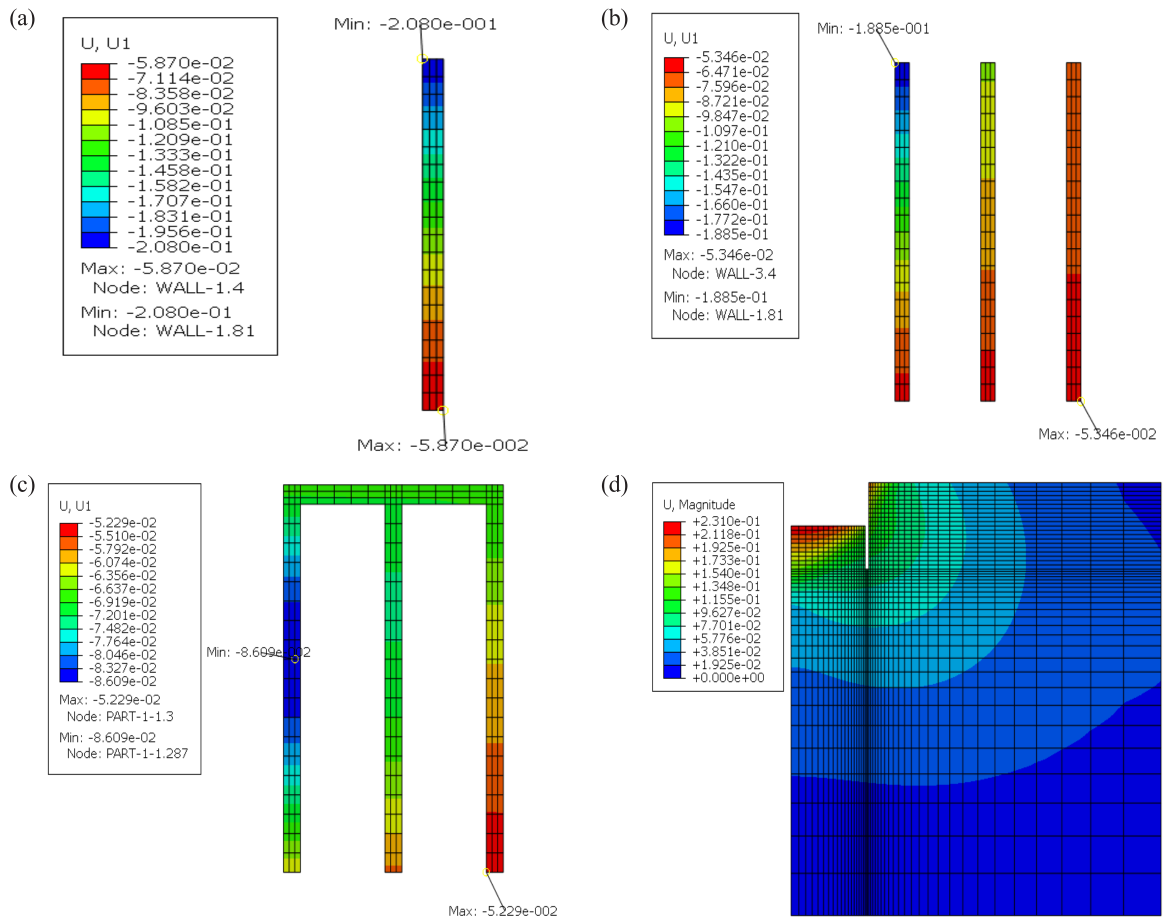


Figure 2. Horizontal displacement contour maps of various retaining structures in U1 direction; (a) Cantilever retaining structure; (b) Three-row cantilever retaining structure; (c) M-shaped retaining system; (d) Soil mass

As illustrated in **Figures 2(a)** to **2(b)**, the maximum horizontal displacements of the single-row and three-row cantilever retaining structures are located at the top, measuring 20.8 cm and 18.85 cm, respectively. The three-row cantilever system exhibits a 10.34% reduction in displacement compared to the single-row configuration.

Figure 2(c) demonstrates that the M-shaped retaining structure, owing to the constraint effect of the connecting beams, shifts the maximum displacement to 8.609 cm, representing reductions of 58.22% and 53.90% compared to the single-row and three-row cantilever systems, respectively. The study demonstrates that: The three-row cantilever system enhances safety relative to the single-row system; The M-shaped retaining structure achieves superior displacement control through the synergistic constraint mechanism of its connecting beams, significantly improving structural reliability. **Figure 3** compares the vertical (S22) stress distribution characteristics between the single-row cantilever retaining structure and the M-shaped retaining structure.

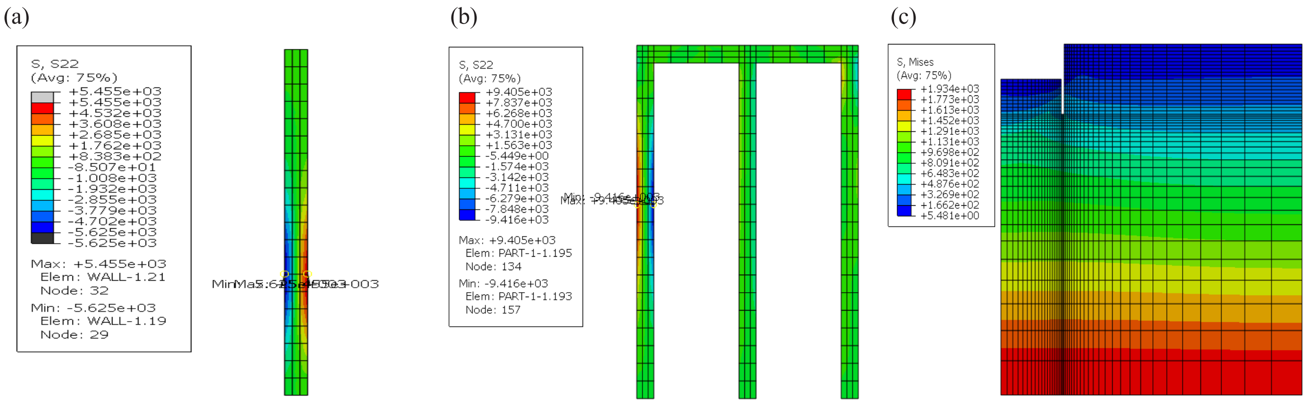


Figure 3. Stress contour maps of various retaining structures in S22 direction; (a) Cantilever retaining structure; (b) M-shaped retaining system; (c) Soil mass

3.2.1. Single-row cantilever system

Maximum compressive stress (5.625 kN) is localized on the left side of the pile body, while maximum tensile stress (5.455 kN) occurs on the right side, both concentrated in the lower two-thirds section. The bending moment diagram exhibits a positive parabolic profile, consistent with the bending behavior of a cantilever beam subjected to uniformly distributed horizontal loading.

3.2.2. M-shaped retaining structure

Owing to the synergistic constraint mechanism of the connecting beams, both maximum tensile stress (9.416 kN) and compressive stress (9.385 kN) are concentrated in the mid-section of the front-row piles. Bending moment magnitudes are significantly higher than those of the single-row system, demonstrating enhanced load redistribution capabilities.

As shown in **Figure 4**, the bending moment distribution of the M-shaped piles differs from that of the single-row configuration. The tops of the front-row piles are subjected to horizontal elastic constraints imposed by the connecting beams, while the soil squeezing effect between the piles exacerbates the bending moment magnitudes. Specifically, when the rear-row piles displace leftward, the soil between the piles is horizontally compressed and cannot heave upward (due to the vertical constraints of the connecting beams), resulting in lateral displacement of the soil near the ground surface. After excavation of the foundation pit, the lateral earth pressure on the left side of the front-row piles decreases, and the soil at the bottom rebounds upward, causing the front-row piles to bend outward due to compression from the mid-section soil. The soil squeezing effect not only disrupts the soil structure but also transmits additional loads to the pile shafts through horizontal displacement, leading to more complex stress concentration phenomena. The results indicate that although the connecting beams optimize displacement control, the pile-soil interaction intensifies localized stress levels.

Figure 5 presents the bending moment diagrams for the three rows of piles in the M-shaped retaining structure.

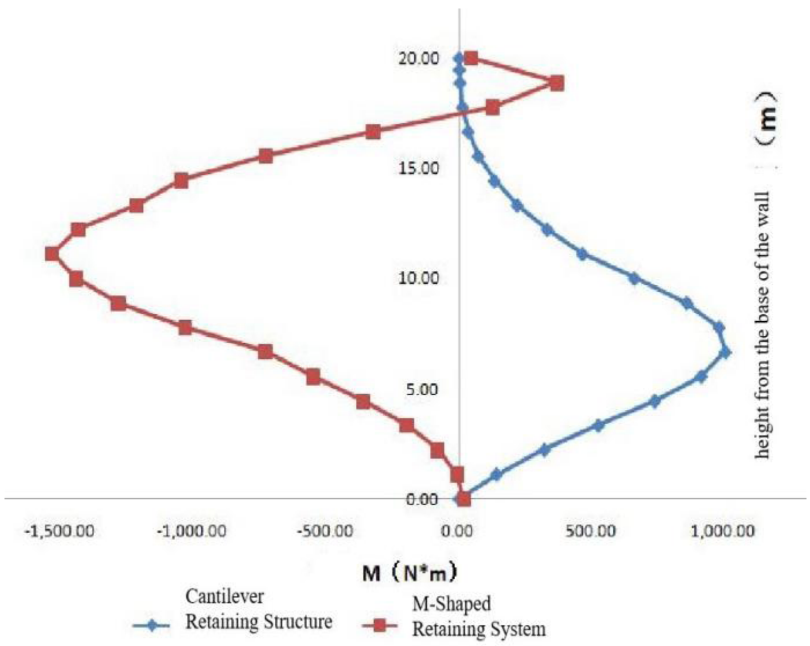


Figure 4. Bending moment diagram of front-row piles

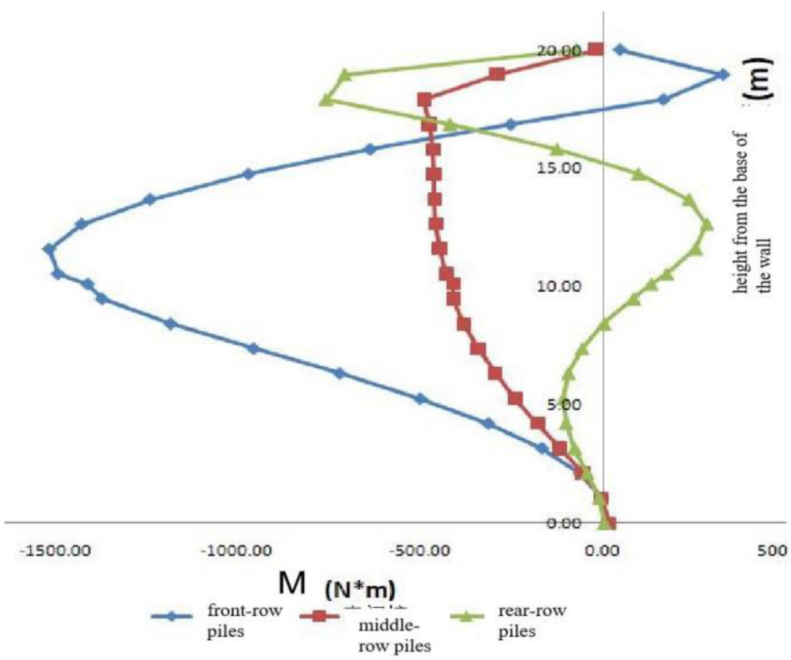


Figure 5. Bending moment diagrams for rows of piles in the m-shaped retaining structure

The maximum bending moments in the three-row pile system are located at the mid-section of the front-row piles. The middle-row piles, subjected to lateral compression from the right-side soil while simultaneously compressing the left-side soil, exhibit a relatively uniform bending moment distribution. Due to the presence of connecting beams, which exert a horizontal tensile force toward the left on the top of the rear-row piles, negative bending moments (indicating tension on the right face) are observed in the upper one-third of these piles. The reduced soil compression on the right side of the rear-row piles compared to their left side results in positive bending moments (compression on the right face) in the mid-section of these piles.

4. Conclusion

This paper presents the modeling process of single-row cantilever retaining structures, three-row cantilever retaining structures, and M-shaped multi-row pile foundation retaining structures established using ABAQUS. The study investigates and analyzes the pile stress distribution, horizontal lateral displacement, and bending moment distribution patterns and behavioral characteristics among various retaining structures employed in foundation pit excavation.

The following conclusions are drawn from the analysis: In deep foundation pit support systems, the M-shaped retaining structure demonstrates optimal safety performance, surpassing both three-row cantilever systems and single-row cantilever systems in effectiveness. For M-shaped piles, the displacement at the pile head decreases with increasing spacing, indicating the existence of an optimal center-to-center spacing for structural stability.

In pile support systems, different structural configurations exhibit distinct bending moment behaviors. For single-row cantilever piles, the maximum bending moment typically occurs just below the excavation face, reflecting the behavior of a classic cantilever beam. In M-shaped retaining structures, the bending moment distribution varies by row. Front-row piles, modeled under fixed-pinned boundary conditions, experience their maximum bending moment above the excavation face. Middle-row piles are subject to uniform tensile stress across the cross-section on the same side, with the peak bending moment occurring at the pile head. Rear-row piles display an S-shaped bending moment distribution, characterized by a positive maximum at the pile head and a negative maximum approximately three-quarters down the pile depth.

Funding

College Students' Innovation and Entrepreneurship Training Program(Project No.: 202310664007), Science and Technology Planning Project of Zunyi City of China (Project No.: Zun Shi Ke He HZ Zi [2022] 121), Guizhou Provincial First-Class Undergraduate Major "Civil Engineering" (Project No.: Qian Jiao Han [2022] No. 61), Guizhou Provincial First-Class Course Construction Project (Project No.: 2022JKXX0165, 2024JKXN0064).

Disclosure statement

The authors declare no conflict of interest.

References

[1] Cai X, 2018, Application of Single-Row Pile Support System in Ultra-Deep Foundation Pit Support in Soft Soil Areas. Construction Technology, 40(6): 830–832+849.

[2] Xiong C, Zhang M, Chen Y, 2022, Experimental Study on H-Shaped Retaining Structures. China Civil Engineering Journal, 55(7): 108–120.

[3] Li Y, Zhang X, Zhang D, et al., 2023, Model Test Study on Mechanical Behavior of H-Shaped Anti-Slide Piles Under Curved Landslide Conditions. Engineering Mechanics, 41(7): 1–12.

[4] Li Y, Xu H, Xu Y, 2021, Influence of Pile Spacing on Mechanical Characteristics of Three-Row Anti-Slide Piles in Rock Accumulation. Subgrade Engineering, (214)1: 98–103.

[5] Zou C, He J, Wu Z, et al., 2022, Numerical Analysis of Load Transfer Mechanism for Wedge-Shaped Piles Based on FLAC3D. Geotechnical Engineering, 36(5): 739–742+759.

[6] Zhang X, 2013, Numerical Analysis of H-Shaped Anti-Slide Piles in Red Bed Landslide Treatment, thesis, University of South China.

[7] Wu M, Sheng J, Tao X, et al., 2017, Three-Dimensional Finite Element Study on the Influence of Anti-Slide Pile Positions on Slope Stability. Mining Research and Development, 37(9): 82–85.

[8] Zhan Z, Xu G, 2020, Numerical Simulation of the Influence of Different Pile Arrangements on H-Shaped Double-Row Pile Support Structures. Safety and Environmental Engineering, 27(3): 193–199.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Research Progress on Risk Assessment in Construction Sites

Shoujuan Cui*

School of Management, Shandong University of Technology, Zibo 255000, Shandong, China

**Author to whom correspondence should be addressed.*

Abstract: Construction work is an important component of social development, and its safety management is crucial for the protection of employees' lives, the efficient development of enterprises, and the social harmony and stability. Therefore, this paper explores the risk identification, risk estimation, risk evaluation, and control strategies of construction sites. It analyzes the research progress, current issues that need optimization, and future development directions, aiming to provide insights for the development of risk evaluation in construction sites.

Keywords: Construction work; Risk identification; Risk evaluation; Construction engineering

Online publication: June 30, 2025

1. Introduction

After the reform and opening-up, the construction industry in China gradually grew and developed at an exceptionally fast pace. Today, the construction industry has become a crucial sector in China's economic development, with a significant impact on societal progress. According to statistics from China's construction industry, there were 151,901 construction enterprises with active projects in 2024. While the industry has developed rapidly, it has also posed certain challenges to the safety management of construction projects, particularly during the construction phase. Compared to other professional activities, the construction industry is one of the most accident-prone sectors in terms of fatalities and injuries, due to its inherent complexity, diverse forms of work, and the high-altitude nature of many tasks. It ranks among the industries with the highest number of safety incidents globally. Therefore, the safety risk assessment of construction sites is of paramount importance. Its objective is to identify, analyze, and quantify potential hazards through a systematic risk assessment approach, and to develop effective risk control measures to reduce the likelihood and consequences of accidents, ensuring the safety, compliance, and sustainability of construction activities.

In 1966, international scholars first discussed safety risk assessment at an academic symposium, and based on this, they developed an initial theoretical framework for safety management. Over the years, many international scholars have applied safety risk assessment methods in various ways to conduct safety management research in the field of construction engineering, yielding a substantial body of work. For instance, Nazeer Ahamed *et al.* studied the safety management status of the Indian construction industry, combining literature reviews and expert interviews to systematically identify 140 human-factor-related errors from three perspectives: senior management, safety supervisors, and workers [1]. This study not only enriched the theoretical framework of human factor-related accidents but also provided significant additions and expansions to the existing literature [2]. Waqar *et al.* studied the seven major obstacles faced by BIM in safety risk management and evaluation applications, considering the complexity of construction. The study indicates that to ensure the safe implementation of projects, it is necessary to enhance technical capabilities, integrate BIM with other risk management frameworks, increase stakeholder participation, and establish a standardized BIM practice system. Wang *et al.* addressed the gaps in existing research on dynamic risk assessment of robotic construction [3]. They examined the entire lifecycle, from site deployment and operational processes to equipment removal.

Through accident causation analysis, they identified 13 risk dimensions and 52 detailed indicators. Using an improved TS-FTA and Bayesian network hybrid modeling approach, they quantified risk intensity and identified three major priorities for improvement: the lack of an effective risk warning mechanism on construction sites, delayed emergency responses to sudden incidents, and the absence of dynamic management of work zones. Their study provides a systematic solution for risk classification and resource optimization in the application of construction robots. Policies such as the "Guidelines for Safety Risk Identification and Control in Construction" and the "Construction Safety Risk Management System" issued by China have also promoted the development and improvement of safety risk identification in construction.

As shown in **Figure 1**, a preliminary programmatic risk assessment process has been developed. First, the various risks that may exist during the construction process are identified. Then, by analyzing the probability of these risks and their potential consequences, a risk evaluation system is established. Based on this, the risk level is assessed by combining the probability and severity of loss. Finally, appropriate risk control strategies and measures are proposed based on the evaluation results. However, research on safety awareness related to human factors remains insufficient, and with the increasing complexity of construction projects and the use of new technologies and materials, there is still a need for further research into the safety risk evaluation of construction sites. Based on existing research findings, this paper provides a systematic review of the main processes of construction site risk assessment, focusing on risk identification, risk estimation, and risk evaluation and control strategies. It also discusses future development trends.

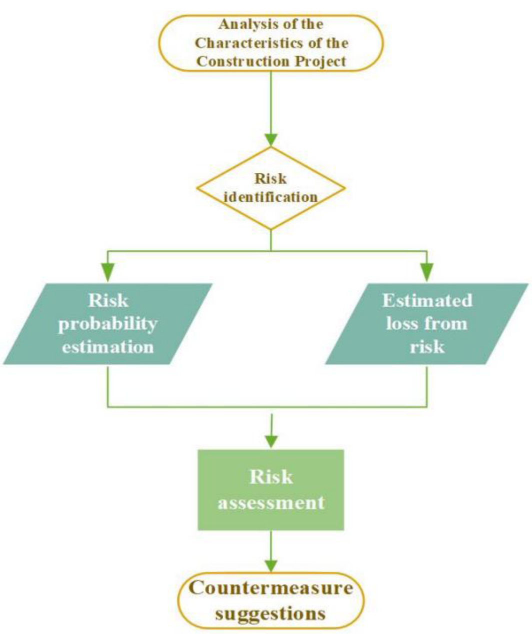


Figure 1. The basic process of risk assessment.

2. Research on risk identification at construction sites

2.1. Overview of risk identification

In 1985, American scholar Haynes first introduced the concept of risk, defining it as the possibility and uncertainty of loss occurring during a certain activity. Risk identification is the first step in construction risk evaluation and forms the foundation of the entire risk evaluation process. Throughout the project's lifecycle, systematically collecting and analyzing relevant information can effectively identify potential risk factors and events, categorizing and assessing them. This process lays the groundwork for subsequent risk control measures. The core purpose of risk identification is to identify and assess the various risks at construction sites, thereby providing a scientific basis for risk management.

2.2. Risk identification methods

The current methods for risk identification are primarily divided into two categories: qualitative analysis and quantitative analysis. Common qualitative methods include literature analysis, the Delphi method, Work Breakdown Structure (WBS), scenario analysis, and Fault Tree Analysis (FTA). However, qualitative methods rely heavily on expert experience and subjective judgment, which may introduce some bias. Quantitative analysis involves accident statistics, a systematic research method based on historical accident data. By collecting and analyzing multidimensional data on accident causes, personnel casualties, economic losses, and other factors, potential future accident risks can be evaluated. In-depth statistical analysis of this data helps identify high-risk factors in specific processes or activities, providing a scientific basis for formulating targeted prevention and control measures. Fault Tree Analysis (FTA) relies on large amounts of complete and accurate data. If the data is insufficient or biased, it can lead to inaccurate analysis results. **Table 1** summarizes and analyzes the advantages and disadvantages of commonly used risk identification methods.

Table 1. Risk identification methods

Risk identification methods	Method characteristics	Advantages	Disadvantages	Applicable scenarios
Literature analysis	Summarizes existing research to identify potential risks related to the subject.	Scientifically rigorous with comprehensive risk coverage.	Time-consuming; may overlook project-specific risks.	Suitable for projects with existing research foundations.
Delphi method	Relies on expert opinions through iterative anonymous feedback to reach consensus.	Flexible and adaptable.	Time-intensive; subjective bias possible	Ideal for complex projects with uncertain risks.
Work Breakdown Structure, WBS	Hierarchically decomposes projects into manageable subcomponents.	Systematic and comprehensive risk identification.	Cumbersome for large-scale projects; high cost.	Effective for structurally defined projects.
Scenario analysis	Simulates multiple scenarios for proactive risk identification	Highly flexible with broad coverage.	Subjective assumptions; resource-intensive.	Suited for uncertain and complex external environments.
Fault Tree Analysis, FTA	Clarifies causal relationships between events via backward deduction.	Qualitative and quantitative integration; logical clarity.	Labor-intensive.	Appropriate for single-risk analysis.
Accident statistics	Analyzes historical accident data for objective insights	Objective with proven preventive value	Data-dependent; lagging indicators	Ideal for high-risk projects requiring quantitative assessment.

2.3. Progress in risk identification research at construction sites

The application of risk identification in construction site safety management has become relatively mature. For example, Tao *et al.* used the WBS-RBS method to conduct a detailed analysis of risk factors at prefabricated structure construction sites [4]. Wang focused on metro construction projects as a case study [5]. Through expert interviews and the Delphi method, he identified 61 risk factors related to equipment upgrade construction risks across four dimensions: personnel, equipment, environmental health, and management, and developed a risk map. Ardeshir *et al.* used Fault Tree Analysis (FTA) to systematically identify risks associated with underground pipeline leakage accidents at construction sites, starting from the "human-machine-material-method-environment" framework [6]. Rabbi *et al.* analyzed 53 articles on the application of AI in construction sites, identifying risk detection as a key area for AI applications in construction safety [7]. By 2025, significant progress will have been made in risk identification at construction sites, particularly with advancements in intelligent systems, big data, and BIM technologies. A systematic and standardized risk identification framework will be gradually perfected, leading to significant improvements in construction safety.

3. Risk estimation at construction sites

3.1. Overview of risk estimation at construction sites

Risk estimation, as the next phase following risk identification, is the process of quantitatively analyzing the identified risk factors. It is the most crucial step in the entire risk evaluation process. To ensure comparability, risk estimation is typically expressed as risk magnitude, which is generally considered to be the product of the probability of risk occurrence and the potential risk loss. In practice, risk estimation methods can generally be divided into three major paradigms: qualitative, quantitative, and integrated analysis, based on differences in analytical dimensions. These methods show significant differences in theoretical foundations, implementation paths, and applicability to engineering projects.

Qualitative analysis methods are typically applied in the early evaluation stage when data is limited. Among them, expert scoring methods use a Delphi-based consultation mechanism to construct interdisciplinary expert groups. These groups rely on domain knowledge to rank risk factors using Likert scales, which is particularly suitable for risk prediction in innovative projects such as high-rise buildings. While this method has the advantage of ease of implementation, its evaluation validity is susceptible to expert cognitive biases and over-reliance on subjective experience. Complementing this, Fault Tree Analysis (FTA) uses deductive reasoning, starting from top events (such as structural collapse) and working backward to basic events. By using Boolean algebra to calculate minimal cut sets, this method provides a visual tool for analyzing risk propagation paths in high-risk scenarios such as tunnel engineering. However, its analytical effectiveness heavily depends on the completeness of historical accident databases.

In new construction scenarios, there may be issues of missing underlying events. The evolution of quantitative analysis methods marks a shift in risk estimation from empirical judgment to mathematical modeling. Monte Carlo simulations create three-dimensional probability models that include random variables such as weather fluctuations and material price variations. By using sampling techniques to generate iterative computations, these models can provide probability distribution curves for risk impacts in complex projects, such as offshore bridges. The accuracy of this method is positively correlated with the computational resources invested. In contrast, the risk matrix method uses a two-dimensional Cartesian coordinate system of probability and consequences to divide risk levels into manageable control zones. This method demonstrates a decision-making efficiency advantage in standardized residential construction projects. The evolution of integrated analysis methods reflects the practical needs of managing complex engineering systems. The Analytic Hierarchy Process (AHP) introduces a judgment matrix using a 9-level scale and combines it with the characteristic root method to solve for the maximum eigenvalue. This approach demonstrates multi-criteria decision-making advantages in carbon emission risk trade-offs in green building projects. The latest improvement, Interval AHP, uses triangular fuzzy numbers to reduce the uncertainty in expert judgment. The Bayesian Network method constructs dynamic conditional probability tables, combined with Gibbs sampling algorithms to achieve parameter learning. This method has successfully reduced the risk warning response time in BIM-enabled smart construction sites.

Current methods of risk estimation at construction sites show three major trends: mixed reality technology based on digital twins is reconstructing the risk simulation paradigm, such as coupling BIM point cloud data with Monte Carlo simulations; machine learning algorithms are being used to optimize the weight distribution process in expert scoring methods; and blockchain technology provides a new path for trustworthy risk data certification. The integration of these technologies not only overcomes the limitations of traditional methods but also drives the transformation of risk management from static evaluation to real-time, intelligent evolution.

3.2. Progress in risk estimation research at construction sites

Due to its simplicity, efficiency, and maturity, expert scoring methods still occupy an important position in risk estimation at construction sites. In identifying risks in shield tunneling construction, Zhou aimed to reduce the subjectivity of expert surveys and the limitations of determining probability [8]. He replaced specific probability values with multiple probability intervals, designing a risk factor survey form based on probability intervals and using expert surveys to calculate the probability distribution of risk factor probability levels. With the development of information technology, BIM technology, which enhances efficiency through technological platforms and standardized processes, has become increasingly mature. Darko analyzed the use of BIM both independently and in combination with other sensing and tracking technologies, as well as 3D model creation and comparison techniques [9]. However, BIM applications in MiCRM still predominantly focus on the design phase, and dynamic risk management requires technological integration. At the same time, there are issues of insufficient multi-source technology integration, a singular risk dimension, and low levels of automation. Currently, there are two major trends in risk identification: the integration of multiple methods and the empowerment of technology. These include the combination of risk matrices with Monte Carlo simulations, as well as the use of the Internet of Things (IoT) and AI to drive dynamic and intelligent evaluations.

4. Research on risk evaluation and control measures for construction sites

4.1. Overview of risk evaluation and control measures for construction sites

In the risk evaluation system, the evaluation stage serves as the core decision-making phase. It defines risk levels and prioritizes control measures based on the results of risk identification and analysis using systematic methods. Specifically, this stage integrates a “probability-severity” two-dimensional assessment model (such as the risk matrix method), numerical calculation methods (such as the LEC method), and multi-criteria decision tools (such as the analytic hierarchy process) to categorize risks into low, medium, and high levels of control. Based on critical project nodes, it matches differentiated response measures. Among them, qualitative methods, due to their ease of operation, are suitable for initial screening, while quantitative methods achieve precise quantification through fault tree probability calculations. Semi-quantitative methods rely on fuzzy mathematical theory to balance subjective and objective evaluation biases. It is worth noting that dynamic evaluation mechanisms empowered by modern technologies, such as BIM-IoT real-time monitoring and data-driven risk threshold warnings, are gradually replacing traditional static evaluation models. These mechanisms establish a closed-loop feedback system of "data collection - threshold determination - level correction." This stage, through the integration of multi-source heterogeneous data and intelligent algorithms, effectively addresses the issues of subjectivity and fragmented data in traditional evaluations, ultimately achieving the visualization of risk status and the scientific allocation of control resources.

Based on a systematic risk management theoretical framework, after identifying and evaluating the levels of risk factors, a multi-dimensional risk prevention and control system should be established to address these risks. This system should systematically integrate preventive control mechanisms, tiered response plans, and continuous education and training programs. By implementing a full-cycle risk management strategy, it effectively controls safety hazards during the construction process. Current research in the field of project management focuses on: using the PDCA (Plan-Do-Check-Act) management cycle to establish a dynamically optimized risk control matrix, building an intelligent early warning system based on BIM technology, and developing tiered and categorized emergency response protocols. Empirical studies show that adopting a prevention-oriented full-cycle management concept, along with modular emergency plans and regular emergency drills, can reduce the occurrence of safety hazards while significantly improving accident response efficiency. Additionally, by establishing a "pre-job certification - on-the-job training - skills assessment" three-level education system, the compliance rate of construction workers' safe operation standards can be significantly increased. This creates a multi-layered protection system that covers the "human-machine-environment-management" four elements, ensuring that risks throughout the entire project lifecycle remain under control.

4.2. Progress in research on risk evaluation and control measures at construction sites

In the field of risk evaluation and control at construction sites, scholars have proposed innovative solutions for different scenarios. To address the issue of frequent accidents caused by weak safety supervision at small construction sites, Na *et al.*developed an AI-based intelligent analysis system using full-cycle aerial imagery data [10]. This system uses multi-objective correlation modeling to intelligently identify fall-risk areas, providing innovative safety control measures for construction projects with limited scale. On the other hand, Chen addressed the challenges of dynamic risk assessment in tunnel underpass projects by constructing a hybrid framework that integrates a trapezoidal cloud model with a Bayesian network [11]. Based on 12 risk indicators, the framework establishes an evaluation system and optimizes the risk parameter discretization and prior probability estimation accuracy through fuzzy membership degree conversion in TCM. The framework also performs multi-dimensional risk simulation and sensitivity diagnosis of key factors, providing targeted solutions. This framework has been validated in the practice of the Wuhan Metro project, demonstrating the improved accuracy of risk level prediction and the effectiveness of real-time dynamic control. It provides an evaluation paradigm that combines algorithmic innovation with practical engineering application value for construction under complex geological conditions.

5. Development trends in risk evaluation for construction sites

With technological innovation, the improvement of policies and regulations, and the deepening of globalization, construction site risks are evolving in multiple dimensions. Intelligent technologies such as BIM, AI, and the Internet of Things (IoT) enhance risk prediction capabilities through real-time monitoring and simulation optimization. However, the application of green materials and complex construction processes has introduced new types of technical risks. The pressure of ESG (Environmental, Social, and Governance) compliance has driven companies to establish full-process management systems, strengthening safety production, and environmental protection standards. Additionally, supply chain fluctuations and labor shortages have exacerbated the risks related to project costs and timelines, promoting the development of automated equipment and resilient supply chains. International construction projects are facing compounded challenges from geopolitical factors, regulatory differences, and extreme environmental conditions, requiring companies to localize their risk management strategies. Moreover, risk control is expanding from the construction phase to the entire lifecycle, including design and operation, with a focus on technological integration and the development of multidisciplinary talents. In the future, risk prevention and control at construction sites will need to integrate technology, management, and policy resources to establish a dynamic, cross-dimensional collaborative mechanism.

6. Conclusion

This review synthesizes significant advancements in construction site risk assessment, encompassing risk identification, estimation, evaluation, and control. While traditional qualitative methods remain foundational, research increasingly focuses on overcoming their limitations, particularly subjectivity and data dependency, through technological integration. The emergence of BIM, IoT, AI, and digital twins enables dynamic, real-time risk monitoring, simulation, and intelligent early warning systems, shifting risk management from static to proactive paradigms. Progress is evident in sophisticated hybrid frameworks for complex scenarios like tunneling or robotic construction, enhancing prediction accuracy and resource optimization. However, challenges persist, including insufficient attention to human-factor safety awareness, fragmented multi-technology integration, and adapting to novel risks from green materials and complex processes. Future development hinges on lifecycle risk management, resilient strategies for global projects and supply chains, and holistic solutions merging technology, policy, and multidisciplinary talent to establish dynamic, cross-dimensional collaborative safety mechanisms. Continuous innovation in risk assessment is crucial for ensuring construction safety and sustainability amidst evolving industry demands.

Disclosure statement

The author declares no conflict of interest.

References

[1] Nazeer Ahamed MF, Mariappan M, 2023, A Study to Determine Human-Related Errors at the Level of Top Management, Safety Supervisors & Workers During the Implementation of Safety Practices in the Construction Industry. Safety Science, 2023: 162.

[2] Waqar A, Othman I, Shafiq N, et al., 2023, Impediments in BIM Implementation for the Risk Management of Tall Buildings. Results in Engineering, 20: 101401.

[3] Wang L, Huang Y, Wang Y, et al., 2025, Comprehensive Lifecycle Safety Risk Assessment for Construction Robotics

Using TS Fault Tree Analysis and Bayesian Network. Automation in Construction, 172: 106041.

[4] Tao Q, Tao C, Wang Y, 2021, Study on Risk Identification Method of Prefabricated PC Structure Building Construction Project. 3rd International Conference on Artificial Intelligence and Advanced Manufacture, 2021: 1219–1224.

[5] Wang T, 2021, Application of Delph Method in Risk Identification of Metro Line Upgrading Construction. Project Management Technology, 19(04): 112–115.

[6] Ardeshir A, Amiri M, Ghasemi Y, et al., 2014, Risk Assessment of Construction Projects for Water Conveyance Tunnels Using Fuzzy Fault Tree Analysis. International Journal of Civil Engineering, 12(4): 396–412.

[7] Rabbi ABK, Jeelani I, 2024, AI Integration in Construction Safety: Current State, Challenges, and Future Opportunities in Text, Vision, and Audio-Based Applications. Automation in Construction, 164: 105443.

[8] Zhou J, Wang H, Wu S, 2013, Risk Analysis of Shield Construction by Polymorphic Bayesian Networks Model. Journal of Tongji University, 41(2): 186–190+202.

[9] Darko A, Chan APC, Yang Y, et al., 2020, Building Information Modeling (BIM)-Based Modular Integrated Construction Risk Management–Critical Survey and Future Needs. Computers in Industry, 123(2): 103327.

[10] Na J, Lee J, Shin H, et al., 2024, Development of Segmentation Technology for Fall Risk Areas in Small-Scale Construction Sites Based on Bird's-Eye-View Images. Sensors & Materials, 36(9): 4017–4028.

[11] Chen H, Shen GQ, Feng Z, et al., 2024, Safety Risk Assessment of Shield Tunneling Under Existing Tunnels: A Hybrid Trapezoidal Cloud Model and Bayesian Network Approach. Tunnelling and Underground Space Technology, 152: 105936.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

An Intelligent Vibration System for Concrete in Nuclear Power Engineering

Yuzhong Han[1], Shiliang Ji[1]*, Pu Chen[2], Yulin Liu[3], Weihong Dong[4], Pengyu Zhang[1]

[1]C+E Center for Engineering Research Test and Appraisal Co., Ltd., Beijing 100142, China
[2]Beijing Information Science and Technology University, Beijing 102206, China
[3]China Nuclear Power Engineering Co., Ltd., Beijing 100840, China
[4]China Nuclear Industry 22ND Construction CO., Ltd., Yichang 443100, China

**Author to whom correspondence should be addressed.*

Abstract: In nuclear power engineering, the quality requirements for concrete are extremely stringent. Concrete structures must exhibit high durability to withstand the effects of nuclear radiation, chemical corrosion, and environmental changes. In particular, nuclear power projects impose higher design standards and safety requirements regarding concrete density. Traditional manual vibration and visual inspection methods are difficult to ensure the required level of concrete compaction. This paper presents an intelligent vibration technology for concrete in nuclear power engineering to enhance construction quality and efficiency. By integrating intelligent sensors, control systems, and data processing algorithms, the technology enables real-time monitoring and evaluation of the vibration process. Results show that intelligent vibration technology effectively ensures the density and uniformity of concrete in nuclear power engineering, thereby improving structural safety and reliability.

Keywords: Nuclear Power Engineering; Intelligent Vibration System; Smart Sensor; Density; Concrete construction

Online publication: June 30, 2025

1. Introduction

Nuclear power engineering projects (such as reactor buildings) carry extremely stringent requirements for concrete quality, as the safety of nuclear power plants during operation is directly related to public safety and the ecological environment. Nuclear power projects are often built near the coast, where salt mist corrosion is severe. Moreover, reactor buildings consist of large volumes of concrete, which require exceptionally high strength and impermeability standards (e.g., C60P8), distinguishing them significantly from civil engineering projects. The concrete structures in nuclear power engineering must possess enhanced durability to withstand the impacts of nuclear radiation, chemical corrosion, and environmental changes, and they must comply with higher design standards and safety requirements regarding the compactness, uniformity, and strength of the concrete.

As the most fundamental material in civil engineering, the quality of concrete construction is directly related to the overall quality of the building structure, with pouring and vibrating playing a crucial role in construction quality [1]. Insufficient vibration can lead to the formation of honeycombs, voids, and cold joints in hardened concrete, while excessive vibration may result in the segregation and uneven distribution of aggregates [2, 3]. In nuclear power engineering, concrete vibration is a key process to ensure that the concrete is fully compacted, directly influencing the sealing and load-bearing performance of the nuclear power plant structure. Insufficient or improper vibration can lead to defects in concrete quality and even pose risks of nuclear leakage. Traditional vibration techniques, which rely on manual labour and lack intelligent control and real-time feedback, struggle to meet the high standards required for concrete quality in nuclear power projects. There are significant quality defects associated with manual vibration, and rectifying these defects post-formation can be costly [4]. Research shows that determining the optimal compaction solely based on the cessation of bubbles on the surface of concrete is not feasible, as it may lead to concrete segregation and compromise quality. Therefore, more online measurement methods should be developed rather than solely relying on surface bubble observation [5]. Currently, intelligent vibration technology includes methods based on vibration depth and location, as well as techniques based on vibration time, all of which enhance vibration quality to a certain extent [6–14]. Therefore, advancing intelligent vibration technology can fundamentally address the fluctuations in concrete construction quality in nuclear power engineering, making it an inevitable choice for the sector to embrace intelligence and high reliability, and serves as an important technical pathway for achieving green construction in line with the 'dual carbon' goals.

2. Theoretical foundation

2.1. Principle of concrete vibration

Generally, freshly mixed concrete belongs to the Bingham fluid, and when the shear stress exceeds the static yield stress of the concrete, the concrete flows, accompanied by the sinking of the aggregate and the upward movement of the enveloping bubbles [15, 16]. From an energy point of view, the energy generated by the vibrator travels in the form of vibrational waves of a certain amplitude and frequency. The greater the energy, the greater the excitation force provided by the vibration rod to the concrete, and the better the concrete flow effect. Within the effective range of vibration, the shear force exceeds the yield stress, the fluidity of the concrete is enhanced, the aggregate sinks, and the bubbles contained in the package float or are vibrated and discharged, so that the slurry is more fully filled and the purpose of compacting the concrete is achieved [16].

2.2. The principle of intelligent vibration compaction technology

The intelligent vibration compaction technology integrates sensors, automated control, and artificial intelligence algorithms to achieve dynamic monitoring, parameter optimization, and precise execution in the concrete vibration process. Its core principles include multi-source data perception, real-time monitoring, and intelligent decision-making. Through the fully integrated process of "perception-analysis-execution-verification", intelligent vibration compaction technology transforms traditional experience-based extensive processes into data-driven precise control, providing innovative solutions for the synergistic optimization of quality, safety, and efficiency in major high-standard projects such as nuclear power.

3. Research on key technologies for intelligent vibration

3.1. Parameter optimization for vibration

The vibration parameters directly affect the compactness, uniformity and construction efficiency of concrete, and the core parameters include vibration time, vibration frequency, amplitude, insertion depth, and vibration radius. Vibration parameter optimization includes multi-source data acquisition, fusion, and parameter optimization algorithms. The former is used to build a dynamic digital twin of the concrete state, the latter employs machine learning and reinforcement learning to train a neural network with historical construction data, predict the parameter requirements under different working conditions, and dynamically adjust the vibration parameters in conjunction with trial-and-error learning to achieve the goal of maximizing compactness.

Based on the real-time data from the sensor, PID control or fuzzy logic is utilized to dynamically fine-tune the parameters, such as automatically extending the vibration time or increasing the frequency when a certain area is detected to be insufficient. The system includes an adaptive learning mechanism, which continuously updates the optimization model through online learning to adapt to changes in the concrete ratio or environmental interference. Furthermore, the optimization experience of vibration parameters from other projects (such as dams and bridges) can be transferred to nuclear power scenarios, and the generalization ability of the model can be enhanced through transfer learning.

3.2. Research and development of vibration system

An intelligent vibration system comprises hardware devices and software control module, as shown in **Figure 1**. The hardware architecture consists of a vibration execution unit and a sensor system, while the software and control module is made up of an intelligent decision-making system and a human-computer interaction interface. The intelligent vibration rod employs piezoelectric ceramic or electromagnetic drive technology, a planetary excitation mode, and high-frequency and low-amplitude vibration, which can actively mitigate the risk of concrete segregation. The rod body is embedded with vibration sensors and fiber grating sensors, which can obtain the main frequency, amplitude, and surface pressure of the vibration rod, and monitor the vibration status (compactness, fluidity, or vibration resistance) of the concrete in real time.

The accelerometer gathers data from the accelerometer, the active power collector gathers active power when the rod vibrates, the voltage stabilizer source is responsible for supplying power to the active power collector, and the depth is obtained by using the positioning module or setting a scale mark on the rod body. The PC is charged with processing the collected data, using the data as input for the energy transfer model, and ultimately achieving the visualization of concrete energy distribution on the host computer software.

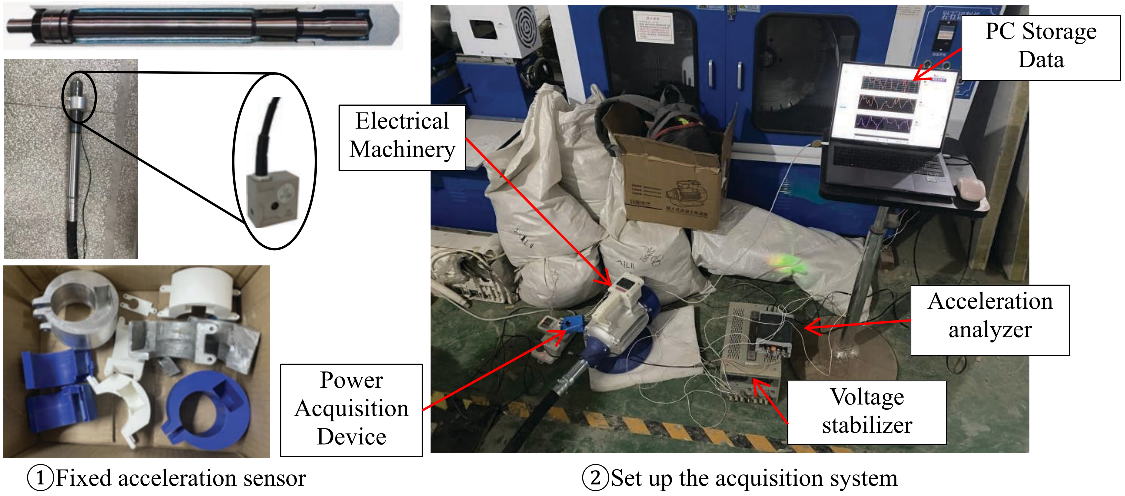


Figure 1. Composition of intelligent vibration system

3.3. Monitoring and evaluation of the stirring process

The intelligent vibration process monitoring and evaluation aims to ensure that the concrete vibration quality meets the high standards of nuclear power engineering through multi-dimensional data collection, real-time analysis, and intelligent decision-making. At present, the sensor network is mainly for vibration monitoring, environmental perception, and equipment status monitoring, which is used to monitor the vibration, pressure change, and temperature change of concrete in real time. The front-end data is preprocessed through the data acquisition module, the data is transmitted to the monitoring center in real time by wired or wireless communication, and the central processing unit analyses the collected data, identifies the vibration state of the concrete, and judges whether the concrete meets the predetermined density requirements by comparing with the set threshold.

As shown in **Figure 2**, the monitoring platform displays the processed data to the operator in a graphical interface, enabling the operator to diagnose in real time. If a vibration parameter is detected that deviates from the preset standard, the system automatically sends a warning or adjustment signal. According to the data feedback, the monitoring system dynamically adjusts the concrete vibration parameters through data-driven and algorithmic models to optimize the vibration effect.

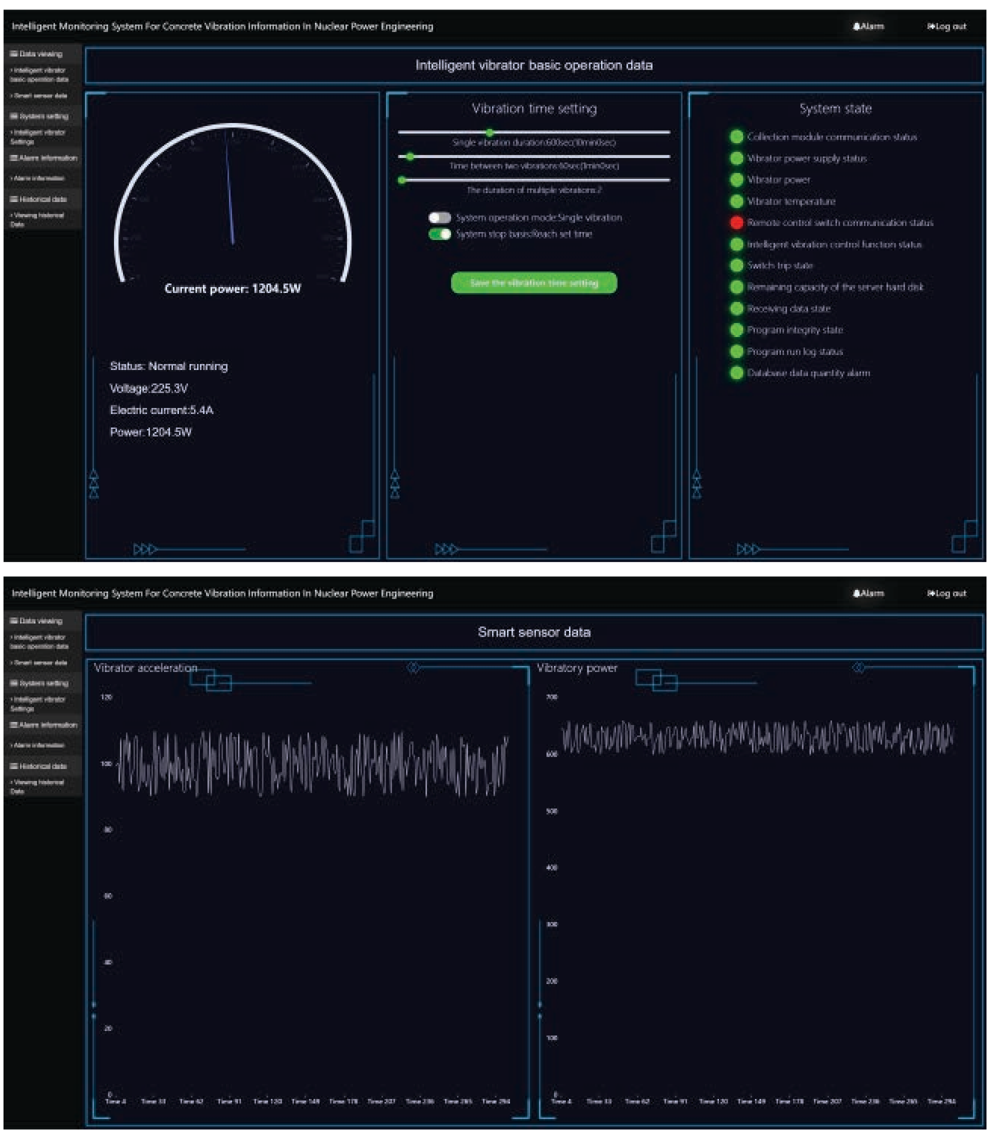


Figure 2. Intelligent concrete vibration monitoring platform

3.4. Evaluation methods for concrete density

Accelerometers, acceleration analyzers, power collection instruments, current transformers, and other equipment were used to obtain specific data on concrete vibration [17]. Based on **Figure 3**, a model for evaluating the compactness of concrete vibration was established using the energy absorption rate calculation method for concrete per unit mass, and the mathematical relationship between vibration parameters and concrete compactness was derived to predict the optimal parameter combination [18]. As shown in **Figure 4**, the energy absorption value is calculated by multiplying the energy absorption rate by the vibration duration, while the range of concrete compaction energy is determined through compressive strength tests of standard specimens, as shown in **Table 1**, for the experiment, C30 concrete from a nuclear island facility was selected, and real-time monitoring of the concrete status during the vibration process was conducted to obtain the distribution of energy absorption rate and energy absorption value per unit mass of concrete under these working conditions.

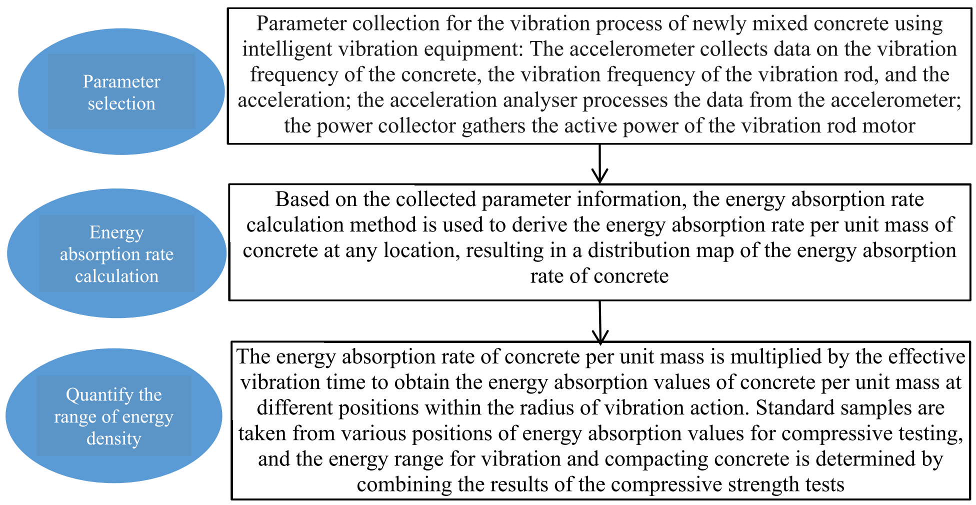
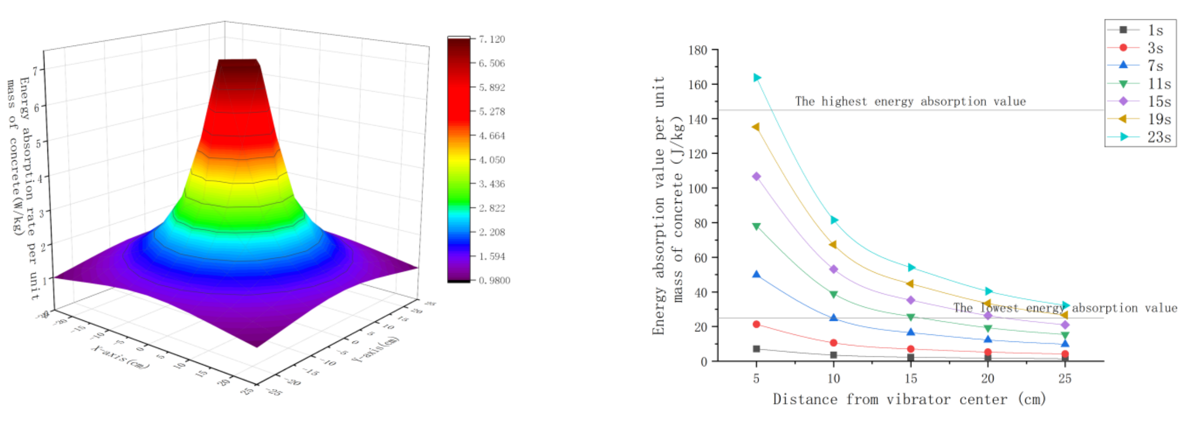


Figure 3. Evaluation process for the effects of vibration and compaction [17]



a. Energy absorption per cm²　　　　b. Energy absorption values per cm²

Figure 4. Analysis on energy absorption

Table 1. List of concrete mix ratios for a nuclear island plant

No.	Strength level	Mixing ratio of raw materials information(kg.m³)						Degree of slump(mm)	Remarks
		Water	Cement P.N	Fly coal ash	Sand	Crushed stone	Water reducing agent		
1	C30	165	264	87	776	1071	3.69–4.74	160 ± 30	5–25 mm Crushed stone

4. Conclusion

This paper integrates advanced sensors, data processing technologies, and automated control systems to optimize vibration parameters and processes. By precisely controlling key parameters during the vibration process, the density and uniformity of concrete in nuclear power engineering can be effectively ensured. The work lays a solid theoretical foundation for implementing intelligent concrete vibration techniques in nuclear power projects.

However, there are still some limitations in this work. The experimental data were obtained in a controlled laboratory setting and have not yet been validated in actual nuclear power engineering projects. Additionally, there are issues regarding the low integration of intelligent devices and the insufficient functionality of the intelligent monitoring system. Future research will address these shortcomings. Furthermore, with advancements in AI, smart construction, and 3D acoustic imaging technology, intelligent vibration systems are expected to evolve toward nano-level defect detection and comprehensive lifecycle performance monitoring. These developments have the potential to systematically resolve the efficiency and quality challenges faced by traditional concrete processes.

Funding

The Advanced Civil Design and Construction Technology Joint LAB of Nuclear Engineering (Project No.: KY23015).

Disclosure statement

The authors declare no conflict of interest.

References

[1] Li L, Wu J, Zhang Y, et al., 2022, Research Progress of Concrete Vibratory Technology. Academic Journal of Science and Technology, 3(2): 71–77.

[2] Tian Z, Bian C, 2014, Visual Monitoring Method on Fresh Concrete Vibration. KSCE Journal of Civil Engineering, 18(2): 398–408.

[3] ACI Committee 309, 1981, Behavior of Fresh Concrete During Vibration. American Concrete Institute, 1981: 1–22.

[4] Tian Z, Ma Y, Li J, 2024, Research Progress on Vibration Compaction of Concrete. Journal of Building Materials, 27(1): 46–57.

[5] Ahmed H, Punkki J, 2024, Surface Bubbles Emergence as an Indicator for Optimal Concrete Compaction. Materials, 17(10): 2306.

[6] Quan Y, Wang X, Liu Y, et al., 2024, Real-Time Monitoring of Concrete Vibration Depth Based on RFID Scales.

Buildings, 14(4): 885.
[7] Gong J, Yu Y, Krishnamoorthy R, et al., 2015, Real-Time Tracking of Concrete Vibration Effort for Intelligent Concrete Consolidation. Automation in Construction, 54: 12–24.
[8] Tian Z, Sun X, Su W, et al., 2019, Development of Real-Time Visual Monitoring System for Vibration Effects on Fresh Concrete. Automation in Construction, 98: 61–71.
Tian Z, Bian C. Visual monitoring method on fresh concrete vibration[J]. KSCE Journal of Civil Engineering, 2014, 18(2):398-408.
[9] Wang D, Ren B, Cui B, et al., 2021, Real-Time Monitoring for Vibration Quality of Fresh Concrete Using Convolutional Neural Networks and IoT Technology. Automation in Construction, 123: 103510.
[10] Li J, Tian Z, Sun X, et al., 2022, Working State Determination for Concrete Internal Vibrator Using Genetic Simulated Annealing Clustering Method. Case Studies in Construction Materials, 17: e01163.
[11] Quan Y, Wang F, 2022, Machine Learning-Based Real-Time Tracking for Concrete Vibration. Automation in Construction, 140: 104343.
[12] Jiang D, Kong L, Wang H, et al., 2024, Precise Control Mode for Concrete Vibration Time Based on Attention-Enhanced Machine Vision. Automation in Construction, 158: 105232.
[13] Li T, Wang H, Tan J, et al., 2024, A Continuous Concrete Vibration Method for Robots Based on Machine Vision with Integrated Spatial Features. Applied Soft Computing, 167: 112231.
[14] Banfill PFG, 1990, Rheology of Fresh Cement and Concrete: Proceedings of the International Conference Organized by the British Society of Rheology, University of Liverpool, United Kingdom.
[15] Wen J, Huang F, Wang Z, et al., 2021, Research Status and Development Trend of Concrete Vibration Technology. Bulletin of the Chinese Ceramic Society, 40(10): 3326–3336.
[16] Li J, Tian Z, 2022, The Invention Relates to a Method and System for Evaluating the Vibratory Compactness of Concrete. Patent No. CN202210511922.3.
[17] China Association for the Promotion of Science and Technology Industrialization, 2022, T/CSPSTC 100–2022, Technical Specification for Intelligent Vibration Construction of Concrete. China Quality and Standards Publishing & Media Co., Ltd, Beijing.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Finite Element Simulation of Mid-Joints in Chuandou-Style Tenon-Mortise Connections of Dong Drum Towers in Guizhou Based on ABAQUS

Ziquan Jiang, Shuang Pu*, Chuanteng Huang, Jilun Cai, Junxiu Liu, Hongyao Tang

School of Engineering, Zunyi Normal University, Zunyi, China

**Author to whom correspondence should be addressed.*

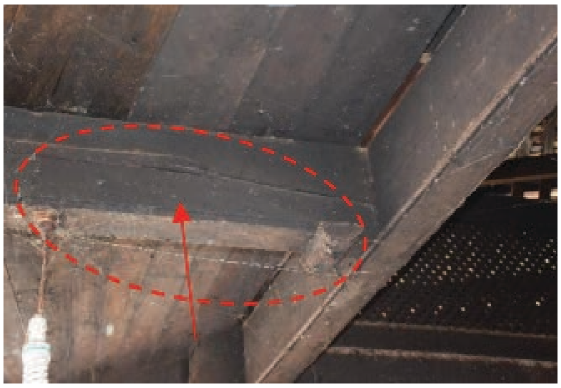
Abstract: As iconic structures in Dong ethnic villages of Guizhou, drum towers hold significant cultural and architectural value. However, research on their mechanical behavior, particularly the mechanical performance of their joints, remains limited, with numerical simulation studies lagging behind theoretical and experimental investigations. This study first establishes an orthotropic elastoplastic constitutive model for timber based on experimental data from Chuandou-style timber structures, determining key parameters such as elastic modulus, shear strength, and plastic strain.Subsequently, a refined finite element model was established using ABAQUS, and its reliability was validated through comparative analysis of stress nephograms, skeleton curves, and other key outcomes with experimental data. The findings provide valuable references for engineering design.

Keywords: Chuandou-style timber structure; Mid-joints in tenon-mortise connections; numerical simulation; ABAQUS

Online publication: June 30, 2025

1. Introduction

As a cultural symbol and core tourism resource in Guizhou Province, the Dong drum towers' structural safety directly relies on the mechanical performance of their Chuandou-style tenon-mortise joints. Existing drum towers commonly exhibit structural deterioration, such as cracking of surrounding beams and column base erosion (**Figure 1**), while newly constructed towers have experienced wind-induced collapse accidents due to structural instability.



(a) Cracking of surrounding beams

(b) Biological degradation at column bases

(c) Cracking of short columns and drainage beams

(d) Cracking of eaves columns

Figure 1. Pathological phenomena in timber structures of dong ethnic historic architecture

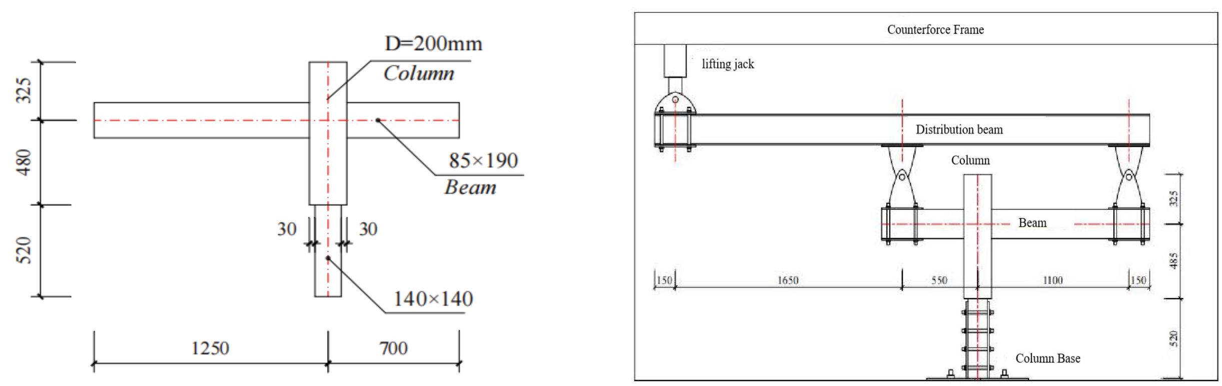
Research on Dong ethnic historic architecture has predominantly focused on architectural and ethnological disciplines in China, while specialized international studies remain notably absent. In terms of artistic value, scholars have dissected the aesthetic significance of drum towers through perspectives such as artistic features, cultural connotations, and decorative totems [1–3]. Cultural semiotic studies further unveil their multifunctional role as carriers of ethnic culture, proposing a "culture-time-space" tripartite framework to conceptualize their spatial essence [4–6]. Significant breakthroughs have been achieved in research on traditional construction techniques: a classification system for drum towers has been established through typological methods, while modular design principles have been integrated to develop modern adaptive pathways for preserving and evolving these craftsmanship traditions [7–9]. The research team in mathematical theory has pioneered the revelation of inherent mathematical regularities in drum towers through geometric configuration and structural logic [10–12]. In the field of structural engineering, research remains in its nascent stage. Scholars have employed finite element simulations to elucidate the energy dissipation mechanisms and stiffness degradation patterns of tenon-mortise joints [13–15].

Furthermore, an orthotropic constitutive model for timber has been established, laying the foundation for seismic performance studies of wooden frameworks [16–18]. Current research exhibits critical limitations in numerical simulations and the mechanical mechanisms of joints, necessitating urgent systematic structural analyses. This study investigates the stress transfer mechanisms of refined mid-joints in Chuandou-style timber frames under static and dynamic loads, grounded in their structural characteristics. By establishing a detailed mechanical model of the tenon-mortise connections, the research elucidates load-path interactions and nonlinear response patterns, thereby providing a theoretical foundation for assessing the overall stability of drum towers and optimizing restoration techniques. The study is designed to achieve dual objectives: safeguarding the structural safety of Dong village residents and perpetuating the intangible cultural heritage (ICH) of traditional timber construction techniques, while concurrently advancing the sustainable development of ethnic tourism economies. These goals align with China's national strategy for low-carbon architectural development.

2. Finite element simulation of mid-joints in Chuandou-style tenon-mortise connections

This section presents the development of a refined finite element analysis model in ABAQUS, grounded in experimental studies on mid-joints in tenon-mortise connections within Chuandou-style timber structures conducted by Li [19].

The test specimen, as illustrated in **Figure 2(a)**, consists of a column with a height of 1325 mm and a diameter of 200 mm, and a transverse beam (Chuanfang beam) measuring 1950 mm in length, 85 mm in width, and 190 mm in height. The column base was fixed during testing, and loads were applied via hydraulic jacks positioned 550 mm left and 1100 mm right from the column center, as depicted in the loading configuration shown in **Figure 2(b)**.



(a) Test specimen model

(b) Specimen loading configuration diagram

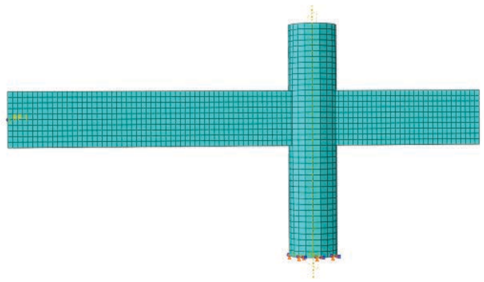
Figure 2. Refined finite element analysis model in test

The material parameters of Chinese fir timber used for establishing the finite element model are summarized in **Table 1**, as compiled from material property tests conducted by Li [19].

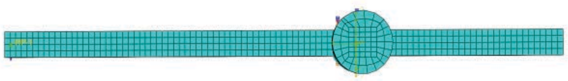
Table 1. Material parameters of Chinese fir timber

Modulus(MPa)		**Poisson's ratio**		**Strength (MPa)**		**Shear strength (MPa)**		**Fracture energy (MPa)**	
E_L	12160	V_{LR}	0.3	σ_{Lt}	79.00	S_{LR}	4.5	G_{fL}	19653
E_R	1400			σ_{Lc}	48.84				
E_T	700	V_{RT}	0.3	σ_{Rt}	4.0	S_{RT}	2.0	G_{fR}	231.8
G_{LR}	912			σ_{Rc}	5.0				
G_{RT}	218.9	V_{LT}	0.5	σ_{Tt}	4.0	S_{LT}	5.0	G_{fT}	231.8
G_{LR}	729.6			σ_{Tc}	5.0				

As illustrated in **Figure 3**, the finite element analysis model of mid-joints in Chuandou-style tenon-mortise connections is presented, with the modeling procedure systematically summarized as follows:



(a) Comprehensive finite element model



(b) Structural characteristics of Chuandou-style Tenon-Mortise Joints

Figure 3. The finite element model of mid-joints in Chuandou-style tenon-mortise connections

(1) Element selection and mesh generation: The transverse beams and mortised columns were modeled using three-dimensional solid elements (C3D8R). The cylindrical geometry at the mortise region was partitioned, and refined meshing was applied to the hollowed section. At the tenon sides where the load-bearing cross-section diminishes, the element size is strictly controlled to less than half of the narrow-edge width, while a nominal mesh width of 20 mm is adopted in bulk regions to ensure computational accuracy.

(2) Operational definition of contact: The normal behavior was defined as hard contact with separation permitted, utilizing the default constraint enforcement formulation; the tangential behavior adopted a penalty friction formulation with an isotropic friction coefficient of 0.4.

(3) Contact interaction establishment: For zero-clearance conditions, surface-to-surface contact pairs were generated through contact pair detection, where the column interface was designated as the master surface and the transverse beam interface as the slave surface. For models with initial gaps, the same surface-to-surface contact formulation was retained, preserving the original master-slave assignments and interaction properties identical to those of the gapless configuration.

(4) Boundary condition configuration: In accordance with the experimental setup conducted by Li, where the lower portion of the column base was intentionally weakened and fixed, the finite element model was configured to simulate a hinged connection at the interface between the upper and lower segments of the column [19]. The modeling process initiated from this hinged section. The column base was idealized as a pinned connection by constraining translational degrees of freedom (U1, U2, U3) and rotational degrees of freedom about the X- and Z-axes (UR1, UR3) to zero, while retaining rotational freedom about the Y-axis (UR2). A tabular amplitude definition was employed, with the amplitude fixed at unity and time-frequency incrementation applied throughout the analysis.

(5) Load application methods:

(a) Monotonic static loading: A rotational amplitude was imposed through boundary condition configuration to simulate continuous rotational displacement loading ranging from 0 to 0.18 rad, achieving kinematic equivalence with experimental hydraulic jack loading protocols.

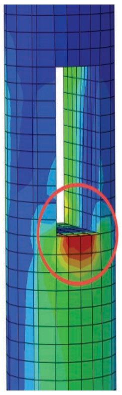
(b) Cyclic loading protocol: Cyclic loading was applied following the displacement-controlled method outlined in Li's study, utilizing the rotational angle-vertical displacement relationship $y=1250\tan\theta$ as the governing criterion [19]. The multi-stage loading protocol comprised: single-cycle phase: 0.03–0.05 rad angular displacement range; three-cycle phase: 0.07–0.13 rad angular displacement range with cumulative loading executed across 15 cycles.

The amplitude-time curve was rigorously aligned with experimental quasi-static test data, ensuring kinematic equivalence in hysteresis response.

3. Analysis of results

3.1. Analysis of monotonic static loading results

As illustrated in **Figure 4(a),** localized compressive deformation is evident beneath the mortise, which aligns with the experimental observations in **Figure 4(b)**. This phenomenon arises from the abrupt increase in interfacial stiffness at the contact zone between the transverse beam and mortise during the continuous downward loading imposed by the hydraulic jack, ultimately inducing significant compressive strains on the mortise underside.

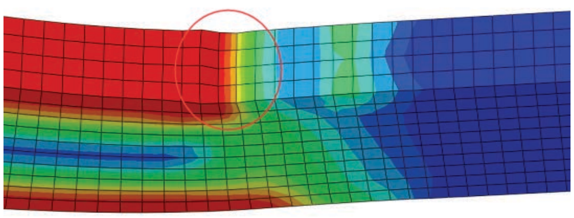


(a) Finite element analysis results

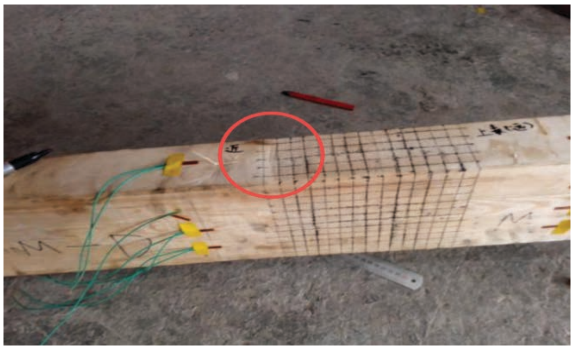
(b) Experimental results

Figure 4. Comparative analysis of mortise deformation under monotonic loading conditions

As shown in **Figure 5**, both experimental and finite element simulation results demonstrate concave deformation at the contact interface between the transverse beam and the mortise. This deformation is attributed to the progressive downward compression of the transverse beam against the column during contact interaction, inducing localized plastic strain accumulation in the mortise region.



(a) Finite element analysis results



(b) Experimental results

Figure 5. Comparative analysis of transverse beam deformation under monotonic loading conditions

As depicted in **Figure 6**, the experimental and finite element analysis (FEA) load-displacement curves exhibit consistent trends (discrepancy $\leq 10\%$), subdivided into two distinct phases: slip-stiffening and slip-plateau. During the initial loading phase, rotational slippage of the transverse beam was induced by negligible force input. Following contact with the mortise-column interface, the system transitioned into a stiffness ascent phase characterized by progressive geometric interlock hardening, which was succeeded by gradual stiffness degradation until eventual stabilization due to orthotropic plasticity saturation in the mortise region.

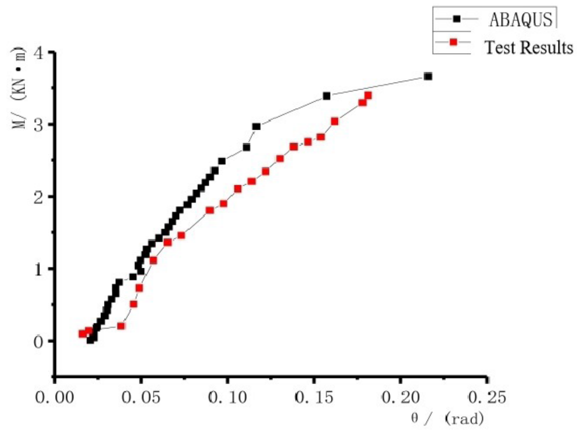
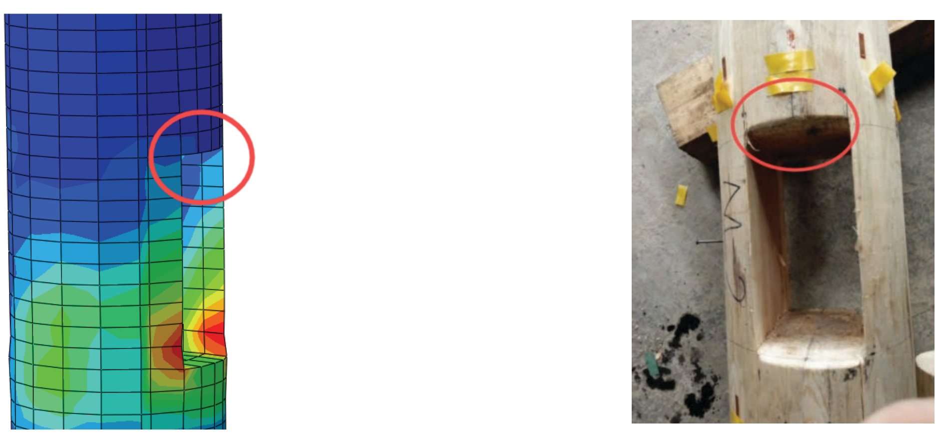


Figure 6. $M-\theta$ Curve of monotonic loading

3.2. Analysis of cyclic loading results

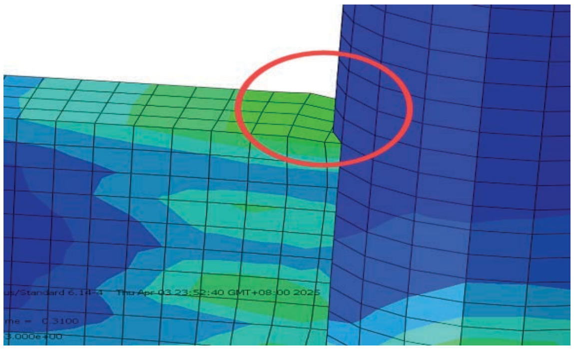
As illustrated in **Figure 7**, both simulation results and experimental data exhibit significant compressive deformation at the upper mortise region, while the deformation magnitude in the lower mortise region remains comparatively minor. This observation aligns with the experimental measurements, confirming consistent deformation patterns across numerical and physical models.



(a) Finite element analysis results (b) Experimental results

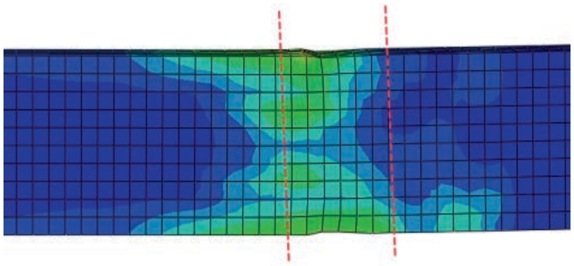
Figure 7. Deformation comparison of mortise-column interface in cyclic loading test

As illustrated in **Figure 8**, pronounced compressive deformation is observed at the contact interface between the transverse beam and mortise in the Chuandou-style mortise-tenon joint. Notably, the longer segment of the transverse beam exhibits greater compressive deformation magnitudes, demonstrating close alignment with experimental measurements. This consistency validates the numerical model's capability to capture localized orthotropic plasticity and stress redistribution mechanisms inherent to traditional timber connections.

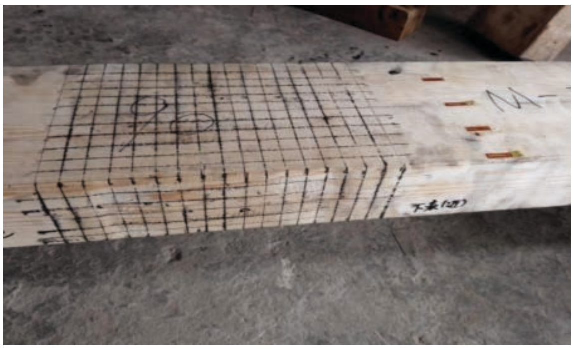


(a) Finite element analysis results 1

(b) Experimental results 1



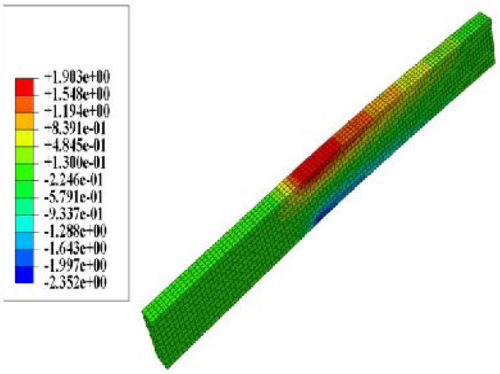
(c) Finite element analysis results 2



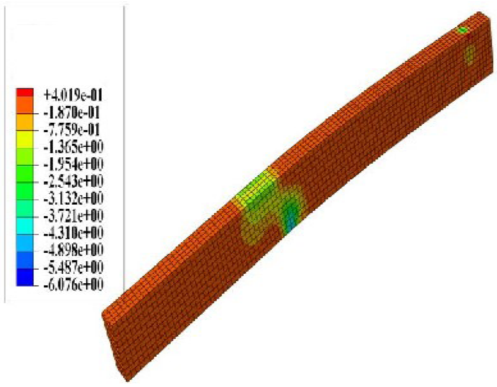
(d) Experimental results 2

Figure 8. Deformation comparison of transverse beams in cyclic loading tests

As shown in **Figure 9**, the stress exerted on the through-tenon beam in the parallel-to-grain direction has not yet reached its critical yield stress, and its mechanical behavior exhibits significant differences compared to that of variable-section straight tenon joints.



(a) Stress nephograms along the grain direction

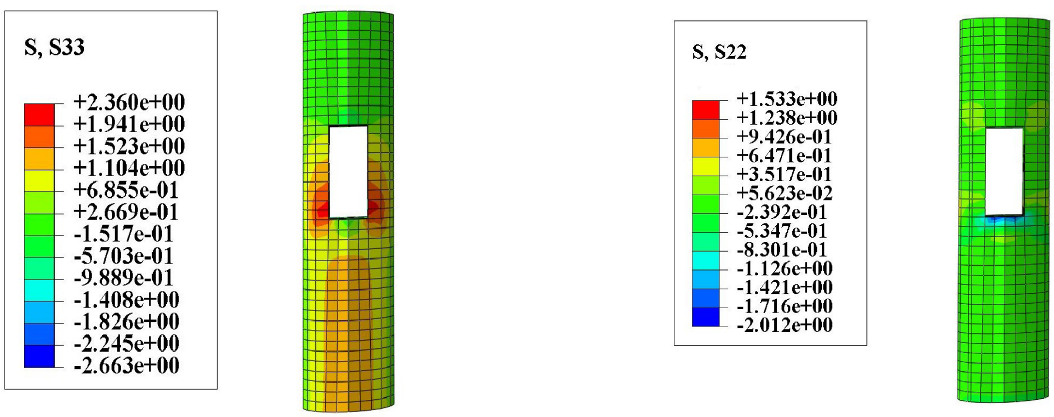


(b) Stress nephograms perpendicular to grain

Figure 9. Stress nephograms of through-tenon beam

This phenomenon indicates that, under a constant cross-sectional configuration of the tenon, the stress in the parallel-to-grain direction remains relatively low, primarily attributed to the absence of compressive loading on the through-tenon beam along this orientation. In contrast, significant yielding is observed in the perpendicular-to-grain direction of the FEA model, indicating that this region has likely entered the plastic deformation regime. The observed stress distribution pattern exhibits a high degree of consistency with variable-section straight tenon joints, a characteristic that strongly reflects the quintessential mechanical behavior inherent to traditional straight tenon joints.

As shown in **Figure 10**, the Chuandou-style mortise-tenon joint column exhibits fundamentally analogous global stress distribution patterns in both longitudinal and transverse grain directions. However, a pronounced cross-sectional reduction is observed in the longitudinal grain direction, accompanied by significantly higher stresses at the mortise openings compared to the transverse grain direction.



(a) Stress nephograms along the grain direction (b) Stress nephograms perpendicular to grain

Figure 10. Stress nephograms of column

As illustrated in **Figure 11**, the skeleton curves of the mortise-tenon joint specimens derived from finite element simulations and experimental literature data exhibit a consistent trend: the bending moment progressively increases with rotational angle.

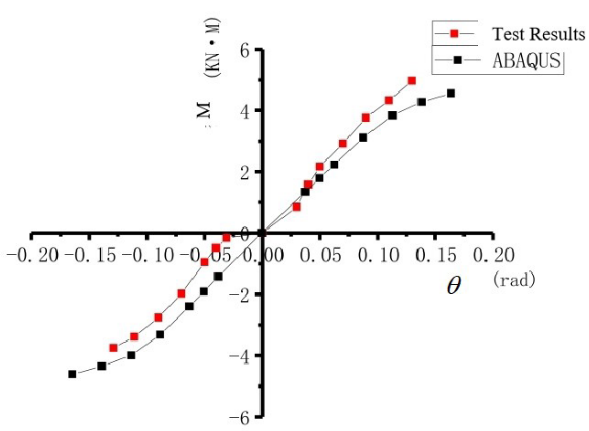


Figure 11. Skeleton curve

Both numerical and experimental results demonstrate analogous behavioral patterns, with an error margin not exceeding 5%. The observed deviations primarily arise from interfacial contact imperfections in experimental joints that fail to achieve the idealized tightness simulated numerically. Fabrication-induced variations during manufacturing processes result in corresponding minor discrepancies in the experimental results.

4. Conclusion

This study presents a refined finite element modelling process for Chuandou-style timber mortise-tenon joints using ABAQUS. The mechanical behaviour of mortise openings and cross beams under both monotonic and cyclic loading was systematically investigated, with emphasis on stress distribution patterns and skeleton curves. The results validate the reliability of the proposed refined finite element model in simulating joint mechanics. The research findings and methodologies can be directly applied to engineering design practices. Furthermore, this framework facilitates subsequent parametric studies to investigate the influence of critical design parameters, such as column diameter, interfacial gap size, and crossbeam width, on the mechanical performance of mortise-tenon joints.

Funding

Science and Technology Planning Project of Zunyi City of China (Project No.: Zun Shi Ke He HZ Zi [2022] 121), College Students' Innovation and Entrepreneurship Training Program (Project No.: 202310664031), Guizhou Provincial First-Class Undergraduate Major "Civil Engineering" (Project No.: Qian Jiao Han [2022] No. 61), Guizhou Provincial First-Class Course Construction Project (Project No.: 2022JKXX0165, 2024JKXN0064)

Disclosure statement

The authors declare no conflict of interest.

References

[1] Liu Y, 2010, Artistic Study of Dong Ethnic Drum Towers, thesis, Guangxi University for Nationalities.

[2] Gao B, 2013, An Anthropological Study of the Artistic World of Dong Drum Towers, thesis, Guangxi University for Nationalities.

[3] Tian X, 2016, Architectural Art of Dong Drum Towers in Southeastern Guizhou, thesis, Guizhou Normal University.

[4] Liu J, 2011, On the Aesthetic Value of Dong Drum Tower Architecture. Art Education Research, 2011: 25.

[5] Liu F, 2012, Construction Techniques and Cultural Significance of Drum Towers in Zhaoqing Dong Community, thesis, Chinese National Academy of Arts.

[6] Xiao J, 2015, Cultural Spatial Connotations of Dong Drum Towers. Journal of Huaihua University, 2015: 6–8.

[7] Liao J, 2007, A Study on the Traditional Cultural Characteristics of the Southern Dong Ethnic Group. Ethnic Publishing House, China.

[8] Ren S, Cheng D, Liang Z, 2008, Architectural Landscapes and Cultural Connotations of Dong Villages. Guangxi Urban Construction, 2008: 36–39.

[9] Wu H, 2010, Cultural Connotations and Social Functions of Dong Drum Towers. Forum on Education and Culture,

2010: 73–77.
[10] Luo Y, 2013, Perspectives on Dong Mathematical Culture. Journal of Mathematics Education, 2013: 67–72.
[11] Zhang H, Luo Y, 2011, Mathematical Culture in Dong Drum Tower Architecture. Journal of Kaili University, 2011: 189.
[12] Wu X, Zhang H, 2020, Investigation of Mathematical Elements in Dong Architecture. Journal of Kaili University, 2020: 1–5.
[13] Qin S, Yang N, Hu H, Zhang L, 2018, Dynamic Characteristics of Damaged Ming–Qing Timber Structures. Journal of Building Structures, 2018: 130–137.
[14] Dong J, Xue J, Sui Y, Xia H, 2019, Hysteretic Behavior and Damage Assessment of Asymmetric Mortise–Tenon Joints in Ancient Timber Structures Under Varying Looseness. Chinese Journal of Applied Mechanics, 2019: 1321–1327, 1519.
[15] Yang N, Tan S, Qin S, 2019, Seismic Vulnerability Analysis of Damaged Ancient Timber Structures. World Earthquake Engineering, 2019: 95–104.
[16] Li Q, 2008, Mechanical Properties and Seismic Resistance of Mortise–Tenon Joints and Timber Frames in Ancient Architecture, thesis, Xi'an University of Architecture and Technology.
[17] Dong C, 2010, Mechanical Behavior and Experimental Study of Mortise–Tenon Connections in Ancient Timber Structures, thesis, Xi'an University of Architecture and Technology.
[18] Sui Y, Zhao H, Xue J, Zhang H, Xie Q, 2010, Experimental Study on Straight Tenon and Dovetail Joints in Ancient Timber Structures. World Earthquake Engineering, 2010: 88–92.
[19] Li P, 2016, Experimental Study on the Seismic Performance of Mortise–Tenon Connections in Chuandou-Style Timber Structures, thesis, Chongqing University.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Research on the Application of BIM Technology in the Architectural Design Phase

Ying Lin*, Juan You

Chongqing Institute of Engineering, Chongqing 400056, China

**Author to whom correspondence should be addressed.*

Abstract: This paper investigates the application of Building Information Modeling (BIM) technology in architectural design and its future developmental trajectories. It begins by elucidating the advantages of BIM technology compared to conventional design methodologies. Subsequently, it examines the specific implementations of BIM technology in architectural design, highlighting its substantial contributions to improving design precision, operational efficiency, and collaborative processes. Lastly, the paper anticipates the evolutionary trends of BIM technology. Looking ahead, as artificial intelligence, blockchain, and big data technologies continue to advance, BIM technology is poised to experience further innovations and breakthroughs, thereby presenting novel opportunities and challenges for the construction sector.

Keywords: BIM technology; Architectural design; Application; Development trend

Online publication: July 1, 2025

1. Introduction

The cost of a construction project throughout its entire life cycle is primarily determined by the design [1]. Achieving the deep integration of design and construction through effective tools and mechanisms has emerged as a critical issue that the contemporary construction industry urgently needs to address. Building Information Modeling (BIM) technology represents an innovative approach based on 3D digital technology, integrating the design, construction, and management of construction projects [2]. With the rapid advancement of modern technology, BIM technology has been extensively adopted in the construction industry due to its robust capabilities in three-dimensional visualization, simulation analysis, and collaborative operations. Since BIM technology effectively resolves issues such as information silos and inadequate communication inherent in traditional design processes, it has progressively become a pivotal tool for optimizing design management [3, 4]. It has significantly shortened the design cycle, minimized design errors, and further promoted the digital transformation of design by incorporating emerging technologies, such as green building simulation and blockchain-based collaboration [5].

2. The application advantages of BIM technology in architectural design

2.1.Three-dimensional visualization

The traditional design approach involves designers utilizing CAD drawing software to represent three-dimensional components in a two-dimensional manner through plane projection. Drawing readers must integrate plans, elevations, details, and other design-related drawings to fully comprehend the designers' intentions. However, deviations may still arise despite these efforts. This necessitates repeated communication and coordination. In contrast, the application of BIM-related software enables the creation of three-dimensional models, which visually present the various components and forms of a building in a three-dimensional format. This facilitates drawing readers' clear understanding of the designers' intentions.

2.2. Complete storability of data information

The traditional two-dimensional design approach relies on graphics or textual annotations to convey architectural information, which often results in difficulties in accurately communicating such information across different stages of the project. In contrast, all components within a BIM model are families that carry parameterized information. By incorporating design parameters into family types, downstream disciplines can extract relevant information directly by selecting the corresponding families. This ensures the completeness and accuracy of project information, thereby facilitating subsequent tasks such as modifications, production and processing, component transportation, maintenance, and debugging [6].

2.3. Real-time coordination

The traditional engineering design approach suffers from several limitations, including delayed design interactions, frequent design changes, and low collaborative efficiency. Due to the independent expression and drawing practices of various disciplines, cooperation and communication among them were restricted, leading to issues not being identified promptly during the design phase. Consequently, construction could not proceed smoothly in later stages, necessitating multiple rounds of plan revisions, which caused delays in the construction schedule and increased costs. The application of BIM technology addresses these challenges by enabling early identification of potential problems during the design stage. It facilitates real-time interaction between drawings and models, ensuring that local modifications to the model are automatically synchronized with related drawings. For example, adjusting the width of moldings in the floor plan will automatically update corresponding elevations, sections, and detailed wall drawings, thus eliminating inconsistencies commonly found in traditional design methods. This enables effective discovery of design issues, optimization of design plan, and ultimately achieve the goal of improving the design quality.

3. The specific applications of BIM technology in architectural design

3.1. Conceptual design and scheme evaluation

In the early stages of architectural design, the design team can leverage BIM-related software to rapidly generate virtual building models. These models enable simulations of various aspects such as appearance, spatial layout, and structural integrity, facilitating an evaluation of the strengths and weaknesses of each design scheme. This process allows decision-makers to conduct a comprehensive cost-effectiveness analysis, thereby providing a robust basis for the final selection of the optimal scheme. Furthermore, the integration of BIM technology with Geographic Information System (GIS) technology enhances site selection and layout optimization. By constructing high-precision three-dimensional terrain models, the undulating topography of the site can be visually represented, aiding in the planning of rational terrain layouts and road directions. Additionally, through the integration of multi-source data, BIM supports simulations of natural conditions such as sunlight exposure, ventilation patterns, energy consumption, and carbon emissions. This capability promotes the harmonious coexistence of buildings with their surrounding natural environments. In practical applications, it also enables the analysis of vegetation distribution and ecological conditions within the site, ensuring the protection of existing ecological resources and minimizing environmental impact.

3.2. Detailed design

During the detailed design phase, BIM technology redefined and optimized the detailed design process. Design information extracted from the model is transformed via standardized interfaces, ensuring accurate descriptions of model attributes. This approach effectively resolves issues such as repetitive modeling and the inability to precisely depict the structural geometry of buildings, thereby achieving true integrated design. For instance, by utilizing interface formats such as CIS/2, DXF, and IFC, designers construct BIM models and perform detailed design tasks using multiple software tools. These interfaces maintain a close link between the abstract analysis model and the BIM model, enabling real-time updates of building information and accommodating the design requirements of various disciplines simultaneously. Structural analysis was conducted using DOE-2 software, energy consumption analysis was performed with ESP-r software, acoustic analysis was executed using Odeon software, and mechanical analysis was carried out using Fluent software.

In addition, within the BIM model, users are able to define a variety of parameters, such as dimensions, materials, height, width, and others, and subsequently apply these parameters to building components, including walls, columns, windows, and so forth. By modifying the values of these parameters, users can efficiently adjust the attributes of the architectural model without the need for manual, individual modifications, thereby enhancing both design efficiency and accuracy. Through parametric design for structural reinforcement, the issue of disorganized parameter information can be effectively mitigated. In the event of design changes, the location and impact of such changes can be visually represented within the model, ensuring the precision and continuity of parameter information transmission and enabling the optimization and adjustment of the reinforcement plan. This process further influences the management and transmission of BIM data in subsequent stages, facilitates interdisciplinary collaboration, allows for the adjustment of relevant design parameters, and ultimately optimizes architectural design.

3.3. Collision detection optimization

During the construction drawing design phase, BIM technology serves as a critical tool for identifying and resolving potential conflicts through its advanced collision detection capabilities. For instance, in mechanical and electrical engineering, numerous specialties and systems such as HVAC, water supply and drainage, fire protection, communication, mechanical equipment, automation, and intelligent systems are integrated. Due to the complexity and density of equipment pipelines, it is imperative to coordinate the spatial relationships among different mechanical and electrical specialties as well as between these specialties and civil structures. By constructing three-dimensional models for all specialties, BIM technology facilitates real-time coordination and conflict detection across multiple disciplines and stages. After ensuring the quality of each specialty model through rigorous self-inspection, the technology integrates these models and conducts comprehensive collision detection.

This process has effectively minimized “errors, omissions, collisions, and deficiencies” among specialties, while also addressing design conflicts and inaccuracies. Research demonstrates that leveraging BIM for collision detection can reduce design changes by approximately 20%, thereby substantially enhancing both design efficiency and quality.

3.4. Green building design in energy conservation and emission reduction

BIM technology can integrate various building performance analysis software to provide a comprehensive assessment of multiple performance indicators, including energy consumption, thermal engineering, sunlight exposure, ventilation, and noise levels. By incorporating relevant software such as Ecotect Analysis, THERM, and Phoenics, designers can simulate the performance of buildings under diverse conditions, thereby gaining an in-depth understanding of their energy consumption, thermal comfort, lighting conditions, air circulation, and acoustic environments. Based on these data-driven insights, designers can optimize architectural form, envelope structure, interior environmental layouts, and material selections, ensuring the effective achievement of energy conservation, emission reduction, and environmental protection objectives.

3.5. Materials and cost control

The integration of BIM technology in material and cost control offers substantial advantages. Specifically, it enables precise calculation of the types and quantities of materials required for construction, thereby providing robust support for procurement processes and effective cost management. Through advanced 3D modeling capabilities, BIM software can automatically generate comprehensive bills of quantities that include detailed specifications, quantities, and location information for all necessary materials. This functionality not only minimizes waste but also optimizes procurement strategies and facilitates cost control. Furthermore, BIM technology empowers designers and project managers to select environmentally friendly and energy-efficient building materials. By incorporating an environmental protection material database, conducting performance simulations, and performing life cycle assessments, materials can be chosen with greater rationality and sustainability. Additionally, through construction simulation, BIM technology allows for a preview of the actual material layout on-site, thus preventing material wastage caused by suboptimal design decisions. Moreover, BIM supports efficient site management and proper handling of leftover materials, enhancing overall material utilization rates. It also enables the simulation and prediction of construction progress, allowing project managers to make informed decisions regarding resource allocation. With the aid of four-dimensional modeling, potential delays and problem areas can be identified in advance, enabling proactive countermeasures to effectively manage and control construction costs.

4. The development trend of BIM technology in architectural design

With the continuous advancement of technologies such as artificial intelligence, blockchain, and big data, the integration of these technologies will become a dominant trend in future development.

4.1. Integration of BIM technology and AI intelligent technology

In structural design, achieving safety while controlling costs requires extensive reference, learning, adjustment, and modification. Under the condition of meeting all rules and constraints, the initial structural calculation model is identified and analyzed through AI to enable intelligent selection of component cross-sectional dimensions and comparison of different structural systems. All potential schemes are calculated and analyzed, and the optimal scheme is generated after a comprehensive evaluation. This allows designers to complete a structurally optimized design that is both safe and economically reasonable within a short time. The rational layout of mechanical and electrical pipelines in the core tube of residential buildings has always been a challenging issue. The arrangement of these pipelines must avoid collisions with building structures, which can be quite complex. With the development of intelligent buildings today, this complexity has significantly increased. By leveraging AI technology, the paths of mechanical and electrical pipelines can be automatically generated, ensuring no collisions with building or structural elements, and solutions can be quickly generated through machine learning algorithms.

By integrating BIM technology with the stable diffusion image generation model, it is possible to produce a variety of transformation effect images with distinct styles in an extremely short time. This not only significantly expands the creative possibilities during the early design phase but also markedly enhances design efficiency. Leveraging its robust image generation capabilities, stable diffusion can rapidly generate preview images of transformation effects that feature intricate details, vibrant colors, and diverse styles based on BIM data inputs. This provides invaluable inspiration and extensive opportunities for conceptual exploration during the project's initial stages. Moreover, this technological synergy has substantially reduced communication costs with property owners. Owners are now able to comprehend the design intent more intuitively, articulate their preferences and modification suggestions promptly, thereby expediting the design iteration process, shortening the project cycle, and fostering the advancement of the architectural design industry toward greater intelligence and efficiency.

4.2. Integration of BIM technology and blockchain technology

BIM technology has been extensively utilized in large-scale architectural design and various related processes. Nevertheless, existing multi-person collaborative design frameworks encounter challenges such as ensuring data security and protecting intellectual property rights. By leveraging a storage approach that combines blockchain with InterPlanetary File System(IPFS), the issue of storing large datasets, such as BIM drawings, within blockchain systems can be effectively addressed [7]. This ensures the security, reliability, and integrity of the data while enhancing the scalability of blockchain technology. Furthermore, this integration provides an advanced solution for data storage and offers a promising direction for resolving the challenges associated with BIM collaborative design.

4.3. Integration of BIM technology and big data analysis technology

Space Syntax is a method for big data analysis that enables the simulation and prediction of thermal flow lines. By leveraging Space Syntax, it becomes possible to model human movement and congregation behaviors within project spaces. Human walking paths are simulated using grid-based systems, and grids traversed by individuals are statistically analyzed to derive insights into crowd congregation patterns. Through advanced big data analytics, the latent value of data can be fully unlocked, thereby providing precise and actionable insights as well as a robust scientific foundation for informed project planning decisions and optimized resource allocation.

5. Conclusion

In conclusion, the application of BIM technology in architectural design demonstrates significant potential and promising prospects. Looking ahead, with the ongoing advancement of technologies such as artificial intelligence, the Internet of Things, and virtual reality, BIM technology will further transform the architectural design process and propel the construction industry toward greater intelligence and sustainability. Nevertheless, challenges related to security, privacy, and standardization must be addressed. Architects and researchers are therefore called upon to collaborate closely, foster continuous innovation, and ensure the steady development of BIM technology within the realm of architectural design, ultimately contributing to a brighter future for both society and the environment.

Funding

Scientific and Technological Research Program of Chongqing Municipal Education Commission (Project No.: KJQN202301907)

Disclosure statement

The authors declare no conflict of interest.

References

[1] Flager F, Adya A, Haymaker J, 2009, AEC Multidisciplinary Design Optimization: Impact of High Performance Computing, thesis, Center for Integrated Facility Engineering (CIFE), Stanford University.

[2] Shi H, Yuan Q, Zhang Y, et al, 2021, Multi-Discipline Forward Collaborative Design Technology Based on BIM Interaction and Data-Driven. Journal of Southwest Jiaotong University, 56(1): 176–181.

[3] Yarmohammadi S, Castro-Lacouture D, 2018, Automated Performance Measurement for 3D Building Modeling Decisions. Automation in Construction, 93: 91–111.

[4] Wang T, Chen H, 2023, Integration of Building Information Modeling and Project Management in Construction Project Life Cycle. Automation in Construction, 150: 104832.

[5] Luo S, Yao J, Wang S, et al, 2022, A Sustainable BIM-Based Multidisciplinary Framework for Underground Pipeline Clash Detection and Analysis. Journal of Cleaner Production, 374: 133900.

[6] Yu W, Jin Y, 2025, Application of BIM Technology in Municipal Engineering Management Under Green Construction Mode. Engineering Construction, 8(1): 54–56.

[7] Han B, Liang Z, Huang Y, et al., 2024, Research on Collaborative Storage of Data Based on IPFS and Blockchain. 2024 IEEE 7th Information Technology, Networking, Electronic and Automation Control Conference (ITNEC), Chongqing, China, 2024: 391–396.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Analysis of the Application of Mechanical and Electrical Equipment Supporting Technology in Coal Mine Filling Mining Face

Sanmin Wang*

China Coal Development Co., Ltd., Beijing 100011, China

**Author to whom correspondence should be addressed.*

Abstract: In the context of increasing demand for coal mine resources in China's current socio-economic development, traditional mining methods have been difficult to effectively meet the requirements of safety production and environmental protection. As a result, coal mine filling mining technology has emerged, which can effectively achieve the goal of controlling surface subsidence in practical applications, while also significantly improving the recovery rate of coal resources. Based on this, this study will first elaborate on the characteristics of filling mining technology, and then analyze the key points of the application of supporting technology for mechanical and electrical equipment in the corresponding working face based on actual cases, in order to provide support for improving the efficiency of coal mining.

Keywords: Coal mine; Filling mining face; Mechanical and electrical equipment

Online publication: July 1, 2025

1. Introduction

With the continuous growth of energy demand and the improvement of environmental protection awareness, coal, as one of China's main energy sources, has important practical significance for the improvement and innovation of its mining methods. Traditional coal mining methods are often accompanied by serious environmental damage and safety hazards such as surface subsidence and gas explosions. Therefore, technicians in the industry have proposed coal mine filling mining technology. By filling the goaf with tailings, paste, and other filling materials, the impact of mining behavior on the surface and ecological environment is effectively reduced, while improving the recovery rate of coal resources. However, it should be noted that coal mine filling mining places high demands on mechanical and electrical equipment at the working face. The relevant equipment not only needs to fully meet the high-efficiency and high-reliability production demands, but also needs to adapt to the special working conditions of the filling material. Therefore, conducting in-depth research and analysis on the supporting technology of mechanical and electrical equipment for coal mine filling mining faces has important practical significance for improving coal mine production efficiency and ensuring safe production.

2. Characteristics of coal mine filling mining technology

After coal resources are mined, if the formed goaf is not handled in a timely manner, it is easy to cause problems such as roof collapse and surrounding rock instability. Therefore, technicians have proposed coal mine filling mining technology. By filling the goaf with materials such as waste stone, tailings, and paste, the originally empty area is tightly occupied. The unique "surrounding rock-filling body" collaborative bearing structure is formed by the interaction between the filling body and the surrounding rock, replacing the cavity formed by traditional caving mining. After the relevant filling material is injected, it can transmit the pressure of the roof, form an active supporting effect on the surrounding rock, effectively inhibit the trend of roof subsidence and collapse, prevent disaster events such as rock bursts and rock explosions, and provide a solid guarantee for safe mining of the mine [1]. In addition, this feature is of great significance for protecting the ecological environment such as surface buildings, water bodies, and farmland, and can minimize the impact and damage of mining activities on the natural environment.

In addition, coal mine filling mining technology can use industrial solid waste such as coal gangue, fly ash, and tailings as filling materials in practical applications. Such materials, which were originally regarded as waste, have gained new applications and value in filling mining technology [2]. By converting relevant solid waste into filling materials, the goal of "using waste to control hazards and exchanging waste for coal" can be achieved, minimizing solid waste accumulation and environmental pollution, and providing a strong guarantee for sustainable mine development and environmental protection.

3. Case overview

To deeply explore the key application points of electromechanical equipment supporting technology in coal mine filling mining faces, this study will select specific cases for detailed elaboration. The mining object of the case filling mining face is the lower coal seam of the Ninth Coal Group. The underground roadway system is arranged such that the return airway is located at an elevation range of +980m to +1002m, while the transportation roadway is distributed at an elevation range of +921.4m to +948m. The mining field extends 538m along the north-south axis, with a width of 130m in the east-west direction, resulting in a total mining area of 69,940 m^2. The average thickness of the coal seam in the coal and rock layer of the filling mining area is 3.5m, with a single and stable structure and a coal seam dip angle of 26.4°. The raw coal belongs to the category of medium-hardness gas coal, with an apparent density index of 1.4t/m^3.

The lithology combination of the roof of the Ninth Coal Group is as follows: a 3.0m thick limestone layer as the immediate roof; an overlying 6.8m thick black mudstone layer; followed by a 2.2m thick interbedded layer of mudstone and fine sandstone, a 2.1m thick fine sandstone layer, a 3.9m thick medium sandstone layer; and finally, a 25.1m thick mixed mudstone layer at the topmost part. Furthermore, a 4.0m thick Fifth Coal Group develops upwards, and the floor consists of a 10.3m thick gray-black mudstone layer.

The case filling mining face extends 538m in the north-south direction and 130m in the East-West direction. Specific reserve data are shown in **Table 1**. The working face adopts an operational mode of five mining cycles per day, with a single advance of 0.6m, and an actual production of 28 days per month. From this, the service life of the mining area can be calculated as follows: service life = total length of the mineable area / monthly planned advance distance = 538m / (0.6m × 5 times × 28 days) = 6.4 months.

Table 1. Mining reserves

Total area	Coal mining average thickness	Coal density	Mining rate	Total storage	Extractable volume	Loss volume
$69940m^2$	3.5m	$1.4t/m^3$	95%	343,000 tons	326,000 tons	17,000 tons

4. Design of supporting scheme for coal mining machine and scraper conveyor

4.1. Design of mining equipment model selection

When planning the collaborative system of mining equipment for the case project, after comprehensive consideration of production efficiency and operational safety factors, it was decided to prioritize the use of a double-roller chainless electrically driven mining machine for coal seam mining operations. Equipment selection needs to meet the following technical indicators:

(1) Cutting roller size: The outer diameter of the roller (D) needs to be calculated based on the maximum mining thickness of the working face (H_{max}), and its mathematical expression is shown in Formula (1):

$$D \geq 0.5H_{\max} \tag{1}$$

Specific work should ensure that the outer diameter of the roller is greater than 50% of the mining thickness. The mining thickness of the case project is 3.5m, so the designed outer diameter of the roller needs to exceed 1.75m. To ensure the coordinated operation of mining machinery and material handling systems, the outer diameter of the roller is finally determined to be 1.8m.

(2) Cutting depth parameter: This indicator has a direct impact on equipment productivity, which is directly determined by conditions such as coal seam thickness, inclination angle, and geological stability [3]. According to engineering practice data, in medium-thick coal seam mining operations, the cutting depth needs to be controlled at 0.8m to achieve the best operating results.

(3) Cutting power configuration: The cutting power of mining equipment (N) is one of the core parameters that affect productivity. Its value depends on the hourly output of the working face (Q), power conversion efficiency (k_1), working condition correction coefficient (k_2), and energy consumption coefficient (k_w). The calculation expression is shown in Formula (2):

$$N = \frac{Qk_w}{k_1k_2} \tag{2}$$

In the case of the filling work face, the value of Q is taken as 650t/h, k_w is usually set to 0.75, and the values of k_1 and k_2 and are taken as 1 and 0.95, respectively. Substituting these values into Formula (2) yields a calculated value of 513kW. Considering the variable underground geological conditions and the high hardness of local coal and rock, appropriate margins need to be reserved when determining the cutting power. The actual configuration scheme adopts dual 300kW motors in parallel drive, increasing the total installed capacity to 600kW.

Besides the core power parameters, equipment selection also requires a focus on key performance indicators such as cutting roller speed, travel speed, and cantilever extension distance [4]. After comparing multi-dimensional parameters, the technical team finally selected the MG300/700-WD mining machine, with specific technical parameter configurations as shown in **Table 2**.

Table 2. Main technical parameters of mining equipment

Project	Parameter	Project	Parameter
Mining height range/m	2.0–4.0	Traction speed/(m/min)	0–10
Adaptable dip angle/(°)	< 40	Rocker arm length/mm	2355
Cylinder diameter/mm	Φ1800	Pump station motor power/kW	12
Cylinder cutting depth/m	0.8	Traction motor power/kW	36 × 2
Cylinder speed/(r/mm)	50	Total weight/t	50

4.2. Design of scraper conveyor selection

When determining the scraper conveyor selection scheme, key indicators such as power configuration, transport efficiency, and central trough structural parameters need to be considered [5]. Based on existing measurement data, the production capacity of coal mining equipment at the working face can reach 650 tons per hour. To ensure the coordinated operation of the conveyor system and coal mining equipment, the transport efficiency of the selected scraper conveyor must exceed the production capacity of the coal mining equipment and maintain an appropriate margin. Therefore, the transport capacity of the conveyor system in the electromechanical equipment scheme for the case's filling mining face needs to be set at 750 tons per hour.

The structural parameters of the central trough directly affect the transport efficiency of the conveyor system. From a theoretical perspective, increasing the size of the central trough can effectively improve the transport capacity, but it is also necessary to consider the maximum power limitations and load-bearing performance of the conveyor device. The determination of the effective load-bearing cross-sectional area (F) of the central trough is based on Formula (3):

$$Q = 3600\, F\eta\gamma v \tag{3}$$

The values of the parameters are: chain operating speed (v) is set to 1.2m/s; the full load coefficient (η) is 0.65; the material looseness (γ) is 0.9; and the designed transport capacity of the conveyor system (Q) is determined to be 750t/h.

Through numerical calculation using Formula (3), the value of F is determined to be 0.3. When a central trough of 1500mm × 750mm × 300mm is selected, the calculation results show a value exceeding 0.3. Therefore, this size scheme is finally determined. In the equipment selection process, besides the size of the central trough, key indicators such as the gear ratio of the reducer, the rated power of the drive motor, and the center distance of the traction chain also need to be examined. After a comprehensive evaluation of multiple parameters, the SGZ730/400 scraper conveyor is finally selected, and the specific technical parameters of the equipment are shown in **Table 3**.

Table 3. Technical parameters of the scraper conveyor equipment

Project	Parameter	Project	Parameter
Conveying capacity/(t/h)	750	Motor power/kW	2×240
Scraper chain type	Medium double chain	Reduction ratio	28.54
Chain speed/(m/s)	1.2	Chain center distance/mm	105
Unloading method	Side unloading at the head	Scraper center distance/mm	800

5. Matching technology for coal mining equipment and scraper conveyors

The coordination between coal mining machines and scraper conveyors involves two main aspects: production capacity coordination and structural adaptation.

In terms of production capacity matching, it is essential to ensure that the coal transportation efficiency of the scraper conveyor is higher than the cutting capacity of the coal mining equipment. This guarantees timely transfer of the mined coal and prevents material buildup underground [6]. Typically, the processing capacity of the transportation system should be maintained within a range of 1.1 to 1.2 times the production capacity of the mining equipment. This configuration not only meets transportation demands but also minimizes idle time of the conveyor system, optimizing economic benefits. In the electromechanical equipment scheme design for the case's filling mining face, the cutting capacity of the mining equipment is set at 650 tons per hour, while the processing capacity of the transportation system reaches 750 tons per hour. The ratio between the two is 1.15, fully complying with the standard range requirement of 110% to 120%.

From the perspective of mechanical structure, the structural coordination between the mining equipment and the transportation system can be described as follows: the coal mining machine is equipped with a cutting roller with a diameter of 1.8 meters and operates with a cutting depth of 800 millimeters. The equipment maintains a safe clearance of 348mm with the scraper conveyor. This design effectively ensures the smooth flow of coal and prevents collisions between the coal mining machine and the conveyor's cable trough during operation.

6. Scheme design for mine ventilation, power supply, and transportation systems

6.1. Mine ventilation system design

According to the current "Coal Mine Safety Regulations" (2016 Revision) and the relevant provisions of the "Code for Design of Coal Industry Mines" (GB 50215-2015), the total ventilation volume of the mine must meet the following two standards: Firstly, based on the maximum number of workers underground, the air supply per person per minute should not be less than $4m^3$; secondly, comprehensive consideration should be given to the air volume requirements of mining faces, chambers, and other areas. Accurate calculations have determined that the total ventilation volume of the mine is set at 115m3/s [7]. The case filling mining face belongs to a gassy mine. In the design, a central parallel ventilation layout and mechanical negative pressure ventilation mode are adopted. The main and auxiliary shafts are responsible for air intake, while the dedicated return air shaft handles air exhaust. The ventilation room of the return air shaft is equipped with two FBCDZN.28/250×2 mine explosion-proof counter-rotating axial flow fans, with one in operation and one as a backup. After rigorous technical verification, this fan system can fully meet the ventilation volume and pressure requirements of the farthest working face in the first mining area.

6.2. Design of the electric power supply system

The case filling work face mainly adopts a four-circuit cable system installed under the auxiliary shaft in the industrial site to transmit electricity to the underground. All four sets of cables are connected to the underground main substation. The downhole cable selects MYJV42-40kV3×240mm2 cross-linked polyethylene insulated power cable, adopting a dual-circuit mutually backup power supply mode. If any power source malfunctions, the remaining two power sources can still effectively ensure continuous and stable operation of all underground equipment. After the system renovation, the underground electrical load has been significantly reduced, and the existing cable configuration fully meets the power supply needs after the renovation.

6.3. Design of the auxiliary transportation system

During the installation of large equipment such as hydraulic supports and coal mining machines, they need to be dismantled first, transported to the bottom of the auxiliary shaft using a cage, and then transferred to a special assembly chamber for hydraulic supports by an explosion-proof battery locomotive. After the equipment is assembled, it is towed by the same type of locomotive to the transfer chamber of the endless rope traction card rail car, and finally, the equipment is transported to the working area through the card rail car system.

(1) Auxiliary shaft transportation system: The total weight of the hydraulic support used in the case filling work face is 51 tons, with dimensions of 8627mm × 3000mm × 1640mm. After actual inspection by technicians, it was found that the current auxiliary shaft lifting device cannot meet the overall transportation demand in terms of carrying capacity, container specifications, and maximum load. Therefore, a split transportation scheme must be adopted. Through detailed calculations, the weight of each component of the disassembled support (including the supporting flatbed truck) is controlled within 29 tons, which fully complies with the technical parameter requirements of the auxiliary shaft lifting system.

(2) Internal mine transportation scheme: In practical work, technicians comprehensively consider factors such as designed production capacity, mining scope, geological characteristics of coal seams, depth of burial, inclination angle, material transportation distance, and total transportation volume of the case filling mining face. They also fully refer to the application status and technical development direction of auxiliary transportation equipment in large and medium-sized mines at home and abroad. The available underground auxiliary transportation equipment mainly includes: endless rope continuous traction device, explosion-proof diesel-powered monorail suspension system, explosion-proof diesel engine-driven rack and pinion transport vehicle, and endless rope traction rack transport system.

After a comprehensive evaluation of the performance characteristics and applicable conditions of various auxiliary transportation equipment, it was finally determined that the West wing auxiliary roadway would use explosion-proof battery-powered electric locomotives as transportation tools, while the working face auxiliary transportation chute would be equipped with an endless rope traction rack car system. From the existing conditions, key systems such as the power supply network and ventilation facilities of the case mining face can fully adapt to the technical requirements of mining technology. Only necessary upgrading and renovation of underground transportation equipment are required to ensure the normal operation of the auxiliary shaft transportation system.

7. Conclusion

In summary, filling mining technology plays an important role in ensuring green and sustainable development in the coal mining industry. To ensure that this technology achieves the expected results, comprehensive consideration of electromechanical equipment configuration is required. In practical work, the case studied in this article carefully designs the supporting scheme for coal mining machines and scraper conveyors. At the same time, it designs mine ventilation, power supply, and transportation system schemes based on the actual situation of the project, and has achieved good results, meeting the actual needs of coal mining. Therefore, its design ideas have strong reference value.

Disclosure statement

The author declares no conflict of interest.

References

[1] Li H, 2021, Discussion on the Application of Installation Technology of Underground Mechanical and Electrical Equipment in Coal Mines. Easy Learning Computers, 2021(009): 1.

[2] Cao Y, 2020, Research and Application of Equipment Selection and Key Mining Technologies for Large Dip Angle Fully Mechanized Mining in Coal Mines. Modern Industrial Economy and Informationization, 010(002): 74–75.

[3] Pan X, 2020, Innovation and Application of Mechanical and Electrical Technology Management in Coal Mines. Chemical Intermediates, 2020(003): 78–79.

[4] Wang L, Wu X, 2023, Research on Equipment Matching and Construction Technology Application of Fast Excavation Equipment Turning and Excavating Cut-Hole in Dafosi Coal Mine. China High-Tech, 2023(14): 133–135.

[5] Zhu M, 2022, Application of Mechanical and Electrical Technology in Coal Mines and Its Automatic Development Direction. Chinese Scientific Journal Database (Abstract Edition) Engineering Technology, 2022(1): 119–122.

[6] Li C, Wang D, Liu C, et al., 2022, Research on the Selection and Matching of Mechanical and Electrical Equipment in Coal Mining Face. Chinese Scientific Journal Database (Citation Edition) Engineering Technology, 2022(7): 199–122.

[7] Meng P, Zhang Y, Yang F, 2020, Equipment Selection and Matching for the 6.5m Large Mining Height Automated Face in Daliu Coal Mine. Coal Mine Mechanical and Electrical Equipment, 41(3): 24–27.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Research on the Construction Path of the Training Model for Applied Talents in the Architecture Major of Universities in the New Era

Huinan Liu, Yukang Cheng

Quzhou University, Quzhou 324000, Zhejiang, China

Abstract: In the context of the new era, deepening education reform and improving the quality of talent cultivation are important measures for universities to align with industry trends and the development needs of students. With the continuous growth of the economy, the construction industry is undergoing rapid development and transformation, and there is an increasing demand for high-quality and high-level applied talents, which poses certain challenges to the architecture majors in universities. Therefore, universities should actively follow the industry development trends and the characteristics of talents, clarify the talent cultivation objectives, optimize the professional teaching system, and promote the high-quality development of education. The cultivation of applied talents in the architecture major of universities is not only an internal requirement for the development of the construction industry but also an important part of the country's innovation-driven development strategy. It is of great significance for promoting scientific and technological progress, enhancing cultural confidence, and promoting the comprehensive development of the economy and society.

Keywords: Interdisciplinary; New era; Architecture; Innovative thinking; Talent cultivation; Industry

Online publication: July 1, 2025

1. Introduction

With the continuous development of society, the construction industry has gradually become a major force in promoting economic development. There is a sharp increase in the demand for applied architecture talents who possess professional knowledge and skills, as well as innovative awareness and design capabilities. In the context of the new era, the development of the construction industry needs to meet the trends of the times and the characteristics of technological development. This requires universities to actively promote the teaching reform process and cultivate more high-level applied talents for the industry. In the new-era context, optimizing the talent-cultivation model for the architecture majors in universities is not only an important measure to improve teaching quality and talent-cultivation quality, but also a crucial topic for enhancing the educational level of universities, keeping up with industry changes, and serving national development. It has far-reaching significance for cultivating high-quality and high-level professionals who meet the development needs of the construction industry.

2. Training requirements for applied talents in the architecture major of universities in the new era

2.1. Mastering advanced information technology tools

With the transformation of the industry and the changes in job requirements, the talent-cultivation objectives of the architecture major in universities have changed. From the perspective of the teaching characteristics of the architecture major, its teaching resources tend to focus on practical teaching, aiming to cultivate students' practical operation ability and problem-solving ability [1]. At the same time, universities should also guide students to maintain a positive learning attitude based on the specific learning situation and talent-development needs, and continuously improve and expand their knowledge systems according to industry changes, to better adapt to the development of the construction industry and lay a good foundation for serving the construction engineering industry.

In addition, with the update and iteration of information technology, the software tools used in the construction industry are constantly changing, including measurement, design, and drawing software. Under such circumstances, university teachers should help students master advanced information technology tools and enable them to have the ability to learn and adapt to new technologies. Finally, in the context of the new era, the talents required by the construction industry should have innovative thinking and learn to transform from a two-dimensional design concept to a three-dimensional building information model, to improve the efficiency and quality of architectural design and contribute to the informatization development of the construction industry [2].

2.2. Improving independent design ability

With the continuous transformation of the construction industry, the demand for applied talents with innovative abilities is increasing rapidly. Universities should deeply integrate the characteristics of industry transformation and talent requirements, so that the talent-cultivation plan must be closely aligned with the actual needs of industry development, and pay attention to the in-depth integration of theory and practice [3]. In particular, it is necessary to strengthen the cultivation of software application ability to meet the constantly improving talent standards in the construction industry. Specifically, on the one hand, students majoring in architecture in universities not only need to deeply understand and master the principles of architectural design, including knowledge in aspects such as space planning, functional layout, and plastic arts, but also should have the thinking and innovative ability for independent design. Teachers can start from practical requirements and help students create aesthetically pleasing and practical design plans by using factors such as graphics, text, and data, and combining multiple dimensions such as the environment, culture, and society [4]. At the same time, students should also be familiar with building structures, building safety, and the performance of building materials. With the assistance of architectural design software, they can design buildings with stability and safety.

On the other hand, in the teaching process of the architecture major, it often involves a lot of interdisciplinary knowledge, such as environmental science, energy efficiency, and interior decoration. Therefore, applied innovative talents in the architecture major should have good interdisciplinary integration capabilities, be able to effectively coordinate knowledge and resources in different professional fields, and achieve the overall optimization of construction projects.

2.3. Meeting industry requirements

With the continuous changes in the construction industry market and technological updates, the construction industry's demand for professionals with professional technical skills, innovative abilities, and interdisciplinary awareness is increasing day by day [5]. This is not only the overall demand of the industry but also the key driving force for promoting the sustainable development of China's construction industry. On the one hand, in the process of cultivating applied architecture talents, universities should closely combine with the actual needs of the industry, closely integrate theoretical knowledge with practice, and improve the teaching efficiency and quality of various links such as architectural design, construction, and management, so that students can better serve the development of the construction industry. On the other hand, architecture talents with application and innovation abilities are the key to promoting the sustainable development and innovation of the construction industry. Such composite talents dare to try more novel technologies, design methods, and design materials, and are sensitive to capturing market and technological changes, promoting the construction industry to develop in a more intelligent, green, and efficient direction.

3. Problems existing in the cultivation of architecture majors

3.1. High proportion of theoretical knowledge explanation

Compared with other majors, the architecture major has certain characteristics such as practicality, comprehensiveness, interdisciplinarity, and applicability. These characteristics indicate that universities should actively carry out practical teaching and increase the proportion of practical teaching. However, according to the current teaching system of the architecture major in universities, the explanation of theoretical knowledge still occupies the main teaching proportion, which has an adverse impact on the cultivation of students' practical abilities [6]. The proportion of practical courses in architecture is low, and it does not cover relevant knowledge such as engineering drawing, field measurement, and model making. As a result, students have difficulty transforming theoretical knowledge into practical operations, thus reducing the teaching effect. In addition, due to the single explanation of theoretical knowledge, students can only passively accept knowledge. Over time, students will form a fixed thinking mode and find it difficult to solve practical problems with the knowledge they have learned. This not only affects the teaching effect but also hinders the talent-cultivation plan of universities to a certain extent, resulting in students' inability to meet the needs of industry development [7].

3.2. Insufficient attention to practical teaching

In the past talent-cultivation system, some universities paid more attention to theoretical knowledge teaching and often ignored the importance of practical teaching, resulting in problems such as imperfect infrastructure for practical teaching, an incomplete curriculum system, and inadequate construction of practical internship bases, which are difficult to meet the development needs of students [8]. At the same time, because architecture courses are highly practical, the lack of practical teaching will affect the cultivation of students' abilities in material perception, understanding of construction details, and on-site management. Moreover, the practical teaching methods are relatively single and traditional, mainly focusing on visits and simple operations, lacking comprehensive and innovative practical projects based on projects and problem-oriented. This is not conducive to cultivating students' innovative thinking and the ability to solve complex problems. Due to limited practical opportunities or practical tasks that do not match students' interests, some students have low enthusiasm and participation in practical sessions and fail to make full use of practical opportunities to improve their abilities.

4. Training strategies for applied talents in the architecture major of universities in the new-era context

4.1. Optimizing the curriculum system and strengthening the effectiveness of professional course teaching

As a comprehensive major, architecture in universities has strong practicality. In order to improve the quality of talent cultivation, universities need to optimize the curriculum teaching system in combination with industry employment requirements, job-specific employment standards, the current situation of courses, and talent-cultivation objectives. In the current teaching modules, some universities divide the curriculum system into three teaching modules: professional foundation, vocational foundation, and disciplinary foundation. According to the systematic principle of the teaching system, the teaching proportion of courses in each module should be scientifically adjusted to increase the importance of practical courses in the cultivation of architecture majors [9]. Take practical teaching as an important part of the curriculum system, so as to strengthen core courses and improve the quality of talent cultivation.

First, while retaining the existing teaching advantages, universities need to sort out and integrate the courses of the architecture major to form an internally related course series, promoting the organic connection and integration of theoretical teaching and practical teaching. This allows students to apply the knowledge they have learned to practical activities while learning professional theoretical knowledge, so as to better improve their practical abilities and further improve the quality of talent cultivation [10]. Second, universities should actively give play to the leading role of architectural design teaching in the entire talent-cultivation process and make architectural design courses a compulsory part of the curriculum system for architecture majors. At the same time, in architectural design courses, teachers should focus on cultivating students' architectural design abilities, especially their independent design abilities after the design plan is determined. For example, teachers can guide students to participate in competitions to exercise their design thinking and adaptability. Finally, teachers can divide the teaching system of architecture courses into three stages. The first stage focuses on cultivating students' basic design abilities, such as hand-drawn sketches and software applications; the second stage gradually increases the complexity and depth of design, such as single-building design and building-group design, to cultivate students' design abilities and innovative thinking [11]; the third stage can cultivate students' professional adaptability and professional qualities in combination with industry requirements. In this way, the curriculum system can be optimized, and the effectiveness of professional course teaching can be improved.

4.2. Implementing the studio teaching model to exercise students' practical application abilities

First, universities should establish a working scene close to the real construction industry according to the development status of the industry and talent requirements, and guide students to conduct practical learning in a real-life scenario. Specifically, universities can cooperate with relevant enterprises to introduce some real projects, allowing students to participate in the entire process from project planning, design, implementation, to evaluation [12]. This enables students to experience a real working environment and exercise their project management abilities. At the same time, universities also need to form a tutor team in each studio, consisting of in-school teachers, industry experts, and designers. These tutors should have rich practical and teaching experience, guide students to complete projects, and help them solve practical problems in the projects, so as to cultivate their professional adaptability and employment competitiveness.

Second, the architecture major in universities has an interdisciplinary nature. In the studio, tutors can encourage students to cooperate with studios of other majors such as structural engineering, environmental design, and urban planning to form interdisciplinary teams and complete projects together. This can not only improve students' comprehensive problem-solving abilities but also cultivate their teamwork spirit [13]. In addition, under the studio teaching model, teachers should pay attention to cultivating students' practical abilities, guide students to independently design works, and comprehensively exercise their design abilities from sketch drawing to 3D modeling and then to physical model making. Teachers should also organize students to conduct on-site inspections of construction sites to understand the construction process and technology, and participate in construction supervision to develop targeted and precise design plans, so as to ensure the quality of the works.

Finally, after the studio teaching model is implemented, university teachers can organize work exhibitions or assessment meetings according to students' performances, allowing students to display their design results and receive evaluations from other students, teachers, and industry experts. This can improve students' expression abilities and self-confidence and help them understand industry standards and market demands. During the implementation of the studio model, universities should deepen cooperation with enterprises to provide students with more realistic teaching resources and advanced practical technologies.

4.3. Utilizing information technology to innovate the teaching model

In the context of the new era, information technology has developed rapidly and been widely applied in various industries, including the education field. The integration of information technology and education and teaching can effectively break the shackles of the traditional teaching system, innovate the teaching model, stimulate students' learning interests, and thus improve the quality of applied-talent cultivation.

First, implement blended teaching. In the process of architecture teaching, teachers should use information technology to integrate diverse teaching resources. According to the teaching characteristics of the architecture major, teachers can use online platforms such as open-network courses, online education platforms, and big-data learning platforms to provide students with rich online learning resources, including teaching courseware, case summaries, and project analyses, to meet the needs of students at different levels and with different interests. At the same time, teachers should also give full play to the advantages of offline classroom teaching. After students have a preliminary understanding of the knowledge, teachers can organize students to answer difficult points in classroom teaching and carry out corresponding practical teaching activities [14]. For example, project-based teaching, case-based teaching, and practical operations can be carried out to transform the theoretical knowledge mastered by students.

Second, adopt the flipped-classroom model. The core of the flipped-classroom teaching model is to center around students. It realizes a flip in teaching forms, teaching processes, and other aspects, so as to cultivate students' autonomous learning abilities and exploration abilities. In the process of architecture teaching, teachers can guide students to use online learning platforms to preview the basic theories and concepts of the course in advance; in classroom teaching, the problems summarized by students can be discussed intensively and practical operations can be carried out, so as to improve the teaching effect and quality [15]. At the same time, teachers can also use the powerful functions of information platforms to solve students' problems online and increase the interaction frequency between teachers and students. Teachers can provide personalized guidance according to students' needs and learning situations.

Third, virtual reality technology and simulation technology in information technology play an important role in improving teaching quality. Teachers can use virtual reality technology and augmented reality technology to construct virtual working environments, allowing students to exercise their skills and conduct practical operations in real-life work scenarios, improving students' understanding of future work and enabling them to better meet the employment requirements of the construction industry.

5. Conclusion

In conclusion, in the context of the new era, in order to better adapt to the transformation and change of the construction industry, universities urgently need to adjust the current teaching system and talent-cultivation plan, and cultivate students into applied talents who can better adapt to industry development and the trends of the times. Therefore, universities can improve teaching quality and talent-cultivation quality by optimizing the curriculum system, implementing the studio teaching model, and utilizing information technology, so as to output higher-quality applied talents for the industry and enable them to better serve the sustainable development of the construction industry.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Liu R, 2025, Exploration on the Teaching Practice of Architecture Courses From the Perspective of the Integration of "Industry–University–Research". Learning Weekly, 2025(11): 7–9.

[2] Yu R, 2024, Ideological and Political Teaching Design of Architecture Courses Under the Background of "Internet+" – Taking the Course Practice of "Architectural Design Principles" as an Example. Internet Weekly, 2024(23): 38–40.

[3] Xiong D, 2024, Research on the Path of the Innovative Development of the Teaching Model of Applied Undergraduate Education Boosted by Artificial Intelligence – Taking the Architecture Major as an Example. Neijiang Science & Technology, 45(11): 97–99.

[4] Huang N, Luo H, Ying Z, 2024, Exploration and Innovation of the "One-Body, Two-Wings" Model for Cultivating Applied Talents in the Architecture Major Under the OBE Concept. University Education, 2024(20): 137–142.

[5] Tang H, Peng L, 2024, Research on the Talent–Cultivation Model of the Architecture Major Based on the Studio System. In: Henan Private Education Association. Proceedings of the 2024 Higher Education Development Forum and Ideological and Political Seminar (Volume I). Hunan Institute of Technology, 2024: 122–124.

[6] Cai C, Shi Q, Jiao L, 2024, Exploration and Practice of the Talent–Cultivation Model for the Architecture Major in Local Applied–Oriented Universities Facing the New Engineering. Industrial Innovation Research, 2024(04): 178–180.

[7] He L, 2023, Research on the Talent–Cultivation Path of the Architecture Major With Mining Characteristics – Taking China University of Mining and Technology (Beijing) as an Example. Journal of Architectural Education in Institutions of Higher Learning, 32(03): 75–83.

[8] Ma M, Li L, Ma Z, 2025, Exploration and Practice of the "Building Structure" Course in the Architecture Major Under the Context of School–Enterprise Cooperation. International Journal of Social Science and Education Research, 8(2): 309–314.

[9] Jiang J, Goepel G, Crolla K, et al., 2024, Impact of Extended Reality on Students' Interest, Self–Efficacy and

Performance in Architecture Education: A Mixed–Methods Research. Advanced Engineering Informatics, 62(PB): 102744–102744.

[10] Zhang H, 2022, Research on the Training Plan for Applied Talents in the Architecture Major of Local Independent Colleges Under the Background of the New Engineering. Heilongjiang Human Resources and Social Security, 2022(09): 100–102.

[11] Zhang N, Hao J, 2021, Exploration and Innovation of the Training Model for Applied Talents in the Architecture Major Under the OBE Concept. Housing Industry, 2021(Z1): 89–91.

[12] Guo J, 2020, Research on the Teaching Reform of the Fifth–Grade Practical Courses in the Architecture Major With the "Three–Joint" Model for Cultivating High–Quality Applied Talents. Chinese Artists, 2020(06): 259 + 261.

[13] Zhai Y, Wang N, Liang X, 2020, Research on the Innovative Cultivation of Architecture Majors in Local Universities Against the Background of Green Architecture. Education Modernization, 7(36): 44–48.

[14] Yao Q, 2020, Discussion on the Training Paths for Architecture Majors Based on BIM Technology. Urbanism and Architecture, 17(11): 62–63.

[15] Yu X, 2020, Research on the Optimization of Professional Foundations in the Training Plan for Applied Architecture Talents Under the Background of New Engineering Construction. Think Tank Era, 2020(12): 210–211.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

BIM Application in Road Construction Sector of Developing Countries

Shuxing Kang*

School of Architecture and Civil Engineering, Jinggangshan University, Ji'an 343009, Jiangxi, China

**Author to whom correspondence should be addressed.*

Abstract: Road construction plays a vital role in the social and economic development of developing countries. However, it is often constrained by financial limitations, maintenance challenges, and environmental concerns. Building Information Modelling (BIM) presents a transformative opportunity to improve road construction efficiency, cost-effectiveness, and sustainability by enabling digital collaboration, lifecycle management, and data-driven decision making. This paper examines the current state of BIM application in the road construction sector of developing countries, focusing on lifecycle integration, economic and operational benefits, and key barriers to adoption. Findings indicate that BIM can enhance project outcomes in whole project life. However, challenges such as high initial costs, lack of skilled personnel, and insufficient policy support hinder widespread adoption. Moreover, the underutilization of BIM in the operational phase leads to unsatisfied returns on investment. The study highlights the critical role of government policies in driving BIM implementation, particularly in public-sector road projects. Recommendations include fostering BIM standards, investing in workforce training, and developing localized BIM solutions to maximize long-term benefits for developing nations.

Keywords: BIM; Road Construction; Application

Online publication: July 1, 2025

1. Introduction

Road constructions are essential to the development of a developing country. They meet people's mobility needs and ensure that goods and resources go to where they are needed [1]. The value of the road network and its contribution to economic growth have long been recognized [2]. For developing countries, most national infrastructure development budget is spent on road construction projects [3]. Ensuring a high level of road construction will benefit the nation's prosperity.

Building Information Modelling (BIM) is a collaborative way of working, underpinned by the creation, collation, and exchange of shared 3D models and intelligent, structured data attached to them. Based on digital technologies, BIM unlocks more efficient methods of designing, creating, and maintaining assets [4]. According to British Standards Institution, BIM uses shared digital data of a built asset to facilitate design, construction, and operation processes, which aims to form a reliable basis for decisions. In road construction, BIM technology can bring a series of benefits like project visualization, clash detection, better onsite collaboration, and better cost estimation to the construction sector [5, 6]. The implementation of BIM technology in road construction will help the construction sector improve project benefits from cost, time, quality, and other aspects.

2. Current status of research

2.1. Implementing BIM throughout the project lifecycle

BIM standards in developed countries emphasize implementing BIM throughout the life cycle. For example, British Standards Institute defined BIM as shared digital data of building assets that form a reliable basis for decision-making for the design, construction and operation process. America National Institute of Building Sciences defined BIM as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its whole life cycle. The Australian Institute of Architects defines BIM as a shared digital representation of physical and functional characteristics of a building which can act as a shared knowledge resource of building information for decisions making during its whole life cycle. This common characteristic is instructive for the road construction sector in developing countries to explore the use of BIM.

Implementing BIM throughout the project lifecycle can bring economic and collaboration benefits. In terms of economy, Azhar *et al*. surveyed 10 projects undertaken by Holder Construction Company and found that the average ROI for using BIM was 634%, which demonstrates the huge potential economic benefits of BIM [7]. In terms of collaboration, in a case study of the Louis Vuitton building project, Eastman *et al*. pointed out that using a cloud-based coordination server and a shared BIM model can help distribute project information and data among the members of a worldwide project team so that helps eliminate many of the problems that commonly derived from poor communication and technological organization [8]. Migilinskas *et al.* and Kjartansdóttir *et al.* also argued that the use of BIM can create a shared, visual flow of information to improve the coordination between project participants, create a more informed design environment, and improve the planning of resources [9, 10].

However, implementing BIM throughout the project lifecycle still faced many obstacles [11]. Scholars have classified these obstacles in much the same way: technology, cost, management, personnel, and legal [5, 12, 13]. Significant obstacles include integrating the different phases of a project's full lifecycle, excessive time and financial cost of learning BIM, insufficient software localization, lack of trained BIM professionals, unfavourable BIM contractual arrangements, lack of BIM standards, and little government guidance [14–17].

2.2. Challenges of road development in developing countries

The problems encountered in the implementation of BIM in road construction in developing countries are sometimes similar to the existing problems in road construction. For example, maintenance issues and financial issues. Understanding the problems of the road construction industry will help to identify the obstacles encountered during the implementation of BIM.

A large number of people in developing countries cannot have reliable roads. Especially in rural areas, many roads are built of dirt or gravel, people's travel can be greatly affected on rainy days. Social and economic development is therefore greatly limited [18, 19].

The main challenges the road sector in developing countries faces include road maintenance issues, financial issues, and pollutant emission issues [20–22]. Lack of road maintenance can lead to huge economic losses. It is estimated that between 1970 and 1990, 85 developing countries in Asia, Africa, and Latin America lost US$45 billion worth of road infrastructure due to inadequate maintenance [23]. Damaged roads and the resulting lack of transport can be an insurmountable obstacle to economic recovery and growth in developing countries [24]. Therefore, high-quality development of roads in developing countries requires attention to road maintenance.

Moreover, facing financial scarcity and a growing need for the road, developing countries needs to prioritize investment in projects that are more necessary and have a higher ROI [25]. Failed investments can have a ripple effect, wasting the money already invested and putting further pressure on the already modest finances of developing countries. For example, in the late 1970s, a number of new roads in Indonesia deteriorated to the point where they needed to be rebuilt because of the loss of funding [26]. The earlier investment was wasted and extra financial contribution was needed to deal with the mess. So it is necessary to ensure that the road project is built with an adequate ROI before starting the project.

Furthermore, pollutant emissions have become a major challenge for the road construction sector in developing countries [27]. There is a great demand for the construction of new roads in developing countries. However, road construction projects have significant emissions that can seriously affect human health and economic equilibrium from the start of project implementation to the demolition phase. A study by Rani *et al.* stated that these pollutants not only cause damage to the human respiratory tract, but also increase the deterioration of rubber, plastic, and paints [28]. The damage would influence the performance of roads. As a result, the roads department would have to carry out more frequent road maintenance, which would lead to a higher cost of road maintenance.

2.3. Benefits of implementing BIM in road construction

The use of BIM in the road construction sector can be divided into three phases: the pre-construction phase, the construction phase, and the post-construction phase.

In the pre-construction phase, BIM can be applied to enhance the automation of cost estimation, assist designers with road design, and integrate design and structural inspection. Park *et al.* developed a cost estimating system based on BIM and GIS [29]. This system will predict possible roads, bridges, and tunnels and their project costs by analyzing terrain cross-sections based on the road alignment. This will enable the owner to select the best route and make sound decisions at the pre-construction stage. Chong *et al.* provided a BIM framework that can analyze pavement structures [30]. The framework visualizes the relationship between the road and its surroundings by bringing together geotechnical and soil conditions, providing a clear picture to assist designers in making appropriate structure design. Tang *et al.* developed a subroutine in Python that combines a 3D road model with adjustable pavement parameters built in Dynamo with the pavement structure analysis software Mechanistic-Empirical Pavement Design Guide, allowing the road structure to be analyzed in a BIM environment [31]. BIM can automatically validate road designs to improve design quality and optimize costs for road construction sectors. In these studies, BIM acts as a bridge to enable other high-tech technologies to be integrated into road design, which will contribute to a high level of road construction.

During the construction phase, BIM can be used to ensure quality, automate deviation detection, and improve site safety. BIM models containing quality and construction information can be viewed on mobile devices to support workers on site in solving process problems [32]. Quality checklists can also be stored in BIM models for use by project managers to improve project management efficiency. A contractor in Shanghai utilized an automated theodolite system integrated with the BIM, visualizing the setting out points and perimeter boundaries and applying laser scanning for automated deviation detection to help increase the accuracy and efficiency of the setting out [30]. In terms of improving construction safety, BIM is able to demonstrate potential safety hazards under a virtual construction platform [31, 33]. The road construction department can use the results of the simulation as a basis for construction site layout to create a safer construction environment.

In the post-construction phase, BIM can be used for road maintenance. For example, Bosurgi *et al.* combined BIM and a crack detection algorithm based on Matched Filtering, scheduling road repairs by automatically identifying road cracks and defects [34]. BIM can also be used for asset management and emergency management. Because BIM provides quick and easy access to all information about the project, asset management can be faster, more accurate, and more informative [35, 36]. And when an emergency happens, BIM can improve the efficiency of the response and minimize any unnecessary risks [37]. These new features from BIM technology will increase the working efficiency and asset management capacity of the road sector and ensure the proper functioning of the road system.

3. Discussion

For the private sector, the main obstacle is that the ROI does not meet the expectations of investors (seen in **Figure 1**). Investment decisions of private sectors are often made based on a considerable ROI. Implementing BIM requires a significant investment in hardware and software. However, the benefits of BIM, such as better collaboration, smoother communication, time saved, and problems avoided are often difficult to quantify or translate into economic benefits. Therefore, the ROI of BIM does not give a complete picture of the benefits of BIM. The ROI calculated by the flawed data will be smaller than it actually is, resulting in a failure to meet investor expectations.

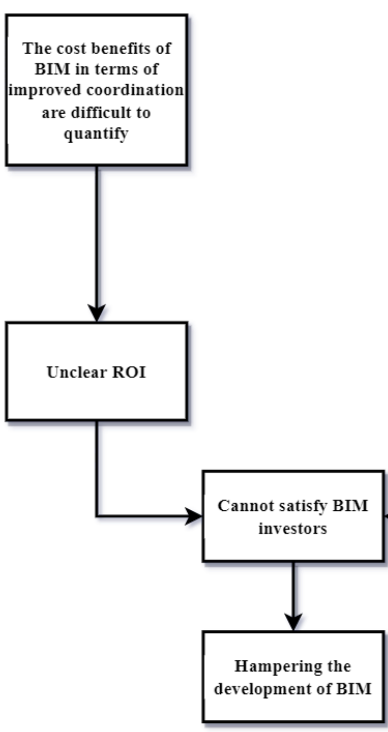


Figure 1. Analysis from the perspective of ROI

Furthermore, the current state of BIM use in developing countries is that BIM is mainly used in the first and middle stages of projects, with little use in later operations. The lack of use of BIM in the operational phase can lead to a lack of full return on the investment in BIM. In the operation phases, the financial benefits of BIM are saving time and cost by providing complete information for project operations and maintenance in an intuitive and easy way in the long term. However, the current low application rate of BIM in the operation phase can result in the benefits of BIM information not being fully utilized. Moreover, the frequency and cost of road maintenance is usually higher than the average level of construction industry. The economic impact of maintenance costs on the operational phase can be even more significant. The influenced overall return on investment of BIM in road construction can lead to the failure of the BIM investment. If BIM is used only in the design and construction phases and not in the operation and maintenance phases, the investment of BIM will become a one-time consumable rather than a long-term investment. This gap can affect the willingness of road developers to invest in BIM and thus hinder the development of BIM in the road construction sector.

While for the public sector, the government's mandatory BIM policy is effective in increasing BIM usage. Because public projects tend to be more responsive to government policy than private projects. The road construction sector in developing countries can take inspiration from this feature. Road projects are often public projects which are quite responsive to policies. So it would be particularly effective in promoting BIM by taking a policy approach.

4. Conclusion

The research demonstrates that the implementation of BIM technology in developing countries' road construction sectors faces two primary obstacles. For the private sector, the main barrier is that the return on investment (ROI) often fails to meet investor expectations. This is partly because many benefits of BIM like improved collaboration, enhanced communication and time savings are difficult to quantify. Additionally, the current limited application of BIM in the operational phase prevents the full realization of BIM investment benefits. If BIM is utilized only in the design and construction phases but not in operation and maintenance, the investment becomes a one-time expenditure rather than a long-term asset, potentially discouraging road developers from investing in BIM technology. For the public sector, the research indicates that mandatory BIM policies effectively increase BIM adoption rates. Public projects tend to be more responsive to government policies than private initiatives. Since road projects in developing countries are predominantly public undertakings, a policy-driven approach would be particularly effective in promoting BIM implementation in this sector.

Based on these findings, this study recommends that governments in developing countries establish mandatory BIM policies specifically targeting public road projects. Furthermore, they should encourage the application of BIM throughout the entire project lifecycle, especially in the operational phase, to maximize investment returns. Additionally, efforts should be directed toward localizing BIM technology, reducing implementation costs, and developing professional expertise to establish a solid foundation for the widespread adoption of BIM in developing countries' road construction sectors.

Disclosure statement

The author declares no conflict of interest.

References

[1] Olaniyi A, 2016, Transportation and National Development: Emphasis to Nigeria. Developing Country Studies, 7(9): 92–104.

[2] Burrow M, Evdorides H, Wehbi M, et al., 2013, The Benefits of Sustainable Road Management: A Case Study. Proceedings of the Institution of Civil Engineers - Transport, 166(4): 222–232.

[3] Kaliba C, Muya M, Mumba K, 2009, Cost Escalation and Schedule Delays in Road Construction Projects in Zambia. International Journal of Project Management, 27(5): 522–531.

[4] UK BIM Task Group, 2012, Industrial Strategy: Government and Industry in Partnership: Building Information Modelling. HM Government, United Kingdom. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/34710/12-1327-building-information-modelling.pdf

[5] Ullah K, Lill I, Witt E, 2019, An Overview of BIM Adoption in the Construction Industry: Benefits and Barriers. In: 10th Nordic Conference on Construction Economics and Organization. Emerald Publishing Limited, 2: 297–303.

[6] Kumar B, Cai H, Hastak M, 2017, An Assessment of Benefits of Using BIM on an Infrastructure Project. International Conference on Sustainable Infrastructure, New York.

[7] Azhar S, 2011, Building Information Modelling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. Leadership and Management in Engineering, 11(3): 241–252.

[8] Sacks R, Eastman C, Lee G, et al., 2011, BIM Handbook: A Guide to Building Information Modelling for Owners, Designers, Engineers, Contractors, and Facility Managers. John Wiley & Sons, 1: 1–682.

[9] Migilinskas D, Popov V, Juocevicius V, et al., 2013, The Benefits, Obstacles and Problems of Practical BIM Implementation. Procedia Engineering, 57: 767–774.

[10] Kjartansdóttir IB, Mordue S, Nowak P, et al., 2017, Building Information Modelling. Warsaw: Civil Engineering Faculty of Warsaw University of Technology, 2017: 1–120.

[11] Huang B, Lei J, Ren F, et al., 2021, Contribution and Obstacle Analysis of Applying BIM in Promoting Green Buildings. Journal of Cleaner Production, 278: 123946.

[12] Sun C, Jiang S, Skibniewski M, et al., 2015, A Literature Review of the Factors Limiting the Application of BIM in the Construction Industry. Technological and Economic Development of Economy, 23(5): 764–779.

[13] Costin A, Adibfar A, Hu H, et al., 2018, Building Information Modeling (BIM) for Transportation Infrastructure – Literature Review, Applications, Challenges, and Recommendations. Automation in Construction, 94: 257–281.

[14] Volk R, Stengel J, Schultmann F, 2014, Building Information Modeling (BIM) for Existing Buildings — Literature Review and Future Needs. Automation in Construction, 38: 109–127.

[15] Akdag S, Maqsood U, 2019, A Roadmap for BIM Adoption and Implementation in Developing Countries: The Pakistan Case. Archnet-IJAR: International Journal of Architectural Research, 14(1): 112–132.

[16] Oraee M, Hosseini MR, Edwards D, et al., 2021, Collaboration in BIM-Based Construction Networks: A Qualitative Model of Influential Factors. Engineering, Construction and Architectural Management, 29(3): 1194–1217.

[17] Bui N, Merschbrock C, Munkvold B, 2016, A Review of Building Information Modelling for Construction in Developing Countries. Procedia Engineering, 164: 487–494.

[18] Burrow M, Evdorides H, Ghataora G, et al., 2016, The Evidence for Rural Road Technology in Low-Income Countries. Proceedings of the Institution of Civil Engineers - Transport, 169(6): 366–377.

[19] Lebo J, Schelling D, 2001, Design and Appraisal of Rural Transport Infrastructure: Ensuring Basic Access for Rural Communities. World Bank Technical Paper, 496: 1–110. http://hdl.handle.net/10986/13911

[20] Marzouk M, Abdelkader E, El-zayat M, et al., 2017, Assessing Environmental Impact Indicators in Road

Construction Projects in Developing Countries. Sustainability, 9(5): 843.
[21] Burningham S, Stankevich N, 2005, Why Road Maintenance is Important and How to Get it Done. Transport Notes Series, TRN-4: 1–10. https://openknowledge.worldbank.org/bitstream/handle/10986/11779/339250rev.pdf?sequence=1&isAllowed=y
[22] Salih J, Edum-Fotwe F, Price A, 2016, Investigating the Road Maintenance Performance in Developing Countries. International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering, 10(4): 444–448.
[23] Harral C, Faiz A, Asif M, 1988, Road Deterioration in Developing Countries: Causes and Remedies. World Bank Policy Study, Washington D.C.
[24] Pojani D, Stead D, 2015, Sustainable Urban Transport in the Developing World: Beyond Megacities. Sustainability, 7(6): 7784–7805.
[25] Righi M, Gardner N, 2016, Sustainable Roads for Fragile States in Africa. Proceedings of the Institution of Civil Engineers - Civil Engineering, 169(5): 17–24.
[26] Younger J, 2013, Development of Road Infrastructure in Indonesia. Proceedings of the Institution of Civil Engineers - Municipal Engineer, 166(3): 167–174.
[27] Abdelkader ME, 2015, Optimizing Construction Emissions for Sustainable Construction Projects. Thesis for: Master of Science, thesis, Concordia University Montreal.
[28] Rani B, Singh U, Chuhan A, et al., 2011, Photochemical Smog Pollution and Its Mitigation Measures. Journal of Advanced Scientific Research, 2(4): 28–33.
[29] Park W, Kang T, Lee Y, 2013, Roadway Preliminary Cost Estimation Prototype Based on BIM and GIS. Korean Journal of Construction Engineering and Management, 14(6): 14–21.
[30] Chong H, Lopez R, Wang J, Wang X, Zhao Z, 2016, Comparative Analysis on the Adoption and Use of BIM in Road Infrastructure Projects. Journal of Management in Engineering, 32(6): 05016021.
[31] Tang F, Ma T, Zhang J, et al., 2020, Integrating Three-Dimensional Road Design and Pavement Structure Analysis Based on BIM. Automation in Construction, 113: 103152.
[32] Bryde D, Broquetas M, Volm J, 2013, The Project Benefits of Building Information Modelling (BIM). International Journal of Project Management, 31(7): 971–980.
[33] Marzouk M, Hisham M, 2013, A Hybrid Model for Selecting Location of Mobile Cranes in Bridge Construction Projects. The Baltic Journal of Road and Bridge Engineering, 8(3): 184–189.
[34] Bosurgi G, Rustica N, Pellegrino O, et al.2019, The BIM (Building Information Modeling)-Based Approach for Road Pavement Maintenance. Proceedings of the 5th International Symposium on Asphalt Pavements & Environment, 48: 480–490.
[35] Wang Y, Wang X, Wang J, et al., 2013, Engagement of Facilities Management in Design Stage Through BIM: Framework and a Case Study. Advances in Civil Engineering, 2013: 1–8.
[36] Husain A, Razali M, Eni S, 2018, Stakeholders' Expectations on Building Information Modelling (BIM) Concept in Malaysia. Property Management, 36(4): 400–422.
[37] Li N, Becerik-Gerber B, Krishnamachari B, et al., 2014, A BIM Cantered Indoor Localization Algorithm to Support Building Fire Emergency Response Operations. Automation in Construction, 42: 78–89.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

An Exploration of Garden Art in “A Dream of Red Mansions”

Youjun Tang*

China Merchants Chongqing Communications Technology Research & Design Institute Co., LTD., Chongqing 400067, China

**Author to whom correspondence should be addressed.*

Abstract: The garden in “A Dream of Red Mansions” represents a blend of Northern and Southern private gardens, the imperial garden (House of Reunion), and folk culture (Paddy-Sweet Cottage). It embodies the maturity of Chinese garden artistry. This paper examines the classical gardening techniques employed in the garden architecture of “A Dream of Red Mansions,” focusing on five aspects: borrowed view, opposite view, framed view, obstructed view, and highlighted view. It explores how the changes in the garden reflect the transformations of the Jia family and the fortunes of its characters. By connecting specific scenes with the characters, it explores the significance of garden names, plant arrangements, and overall layout, analyzing how these elements reflect the personalities and destinies of the garden’s inhabitants. From the character of the garden to the characters within it, the evolution of the garden mirrors the lives of its inhabitants, reflecting their personal histories, emotional journeys, and the eventual rise and fall of their fortunes.

Keywords: Landscape; Character; Layout; Gardening; Change

Online publication: July 1, 2025

1. Introduction

“A Dream of Red Mansions” is like an encyclopedia of Chinese feudal society. It shows detailed social customs, classical poetry and songs, and brings together many ideas, traditions, and skills of the time. It is a result of deep cultural heritage. In this beautiful work, the garden is like a shining pearl in a crown, quiet but full of meaning. It not only displays the undulating and exquisite pavilions, terraces, and towers, focusing on the deep and serene flowers and trees, but also possesses human-like dispositions, embodying the mysterious shyness and delicacy of the girls in the garden.

From the perspective of classical Chinese gardens, a garden is a beautiful natural environment and recreation area created through the use of engineering techniques and artistic means in a certain geographical area, by transforming the terrain (or further building mountains, stacking stones, and managing water), planting trees, flowers, and grass, constructing buildings, and arranging garden paths.

The development of Chinese gardens has progressed from simple to complex, with increasingly perfect functions, more reasonable layouts, and more exquisite craftsmanship. It developed from the early form of “You” in the Shang and Zhou dynasties to the peak of palace and private garden design in Jiangnan during the Ming and Qing dynasties. The gardens are geographically divided into Northern gardens, Jiangnan gardens, and Lingnan gardens.

Analyzing the historical background of the author of “A Dream of Red Mansions”, the era in which the novel is set is the mid-18th century during the Qing Dynasty. The Qing Dynasty was both a continuation of the feudal system and the dynasty that saw its collapse and ultimate demise. From this historical perspective, the gardens in “A Dream of Red Mansions” have their unique characteristics. The years from 1763 to 1911 mark the late maturity stage of classical Chinese gardens. The gardens in “A Dream of Red Mansions” are not purely Northern or Jiangnan in style. During the reigns of Emperors Kangxi and Qianlong, frequent Southern tours exposed the court to the elegance of Jiangnan landscapes. Thus, when building royal gardens, they consciously incorporated famous scenic spots from Jiangnan, organically fusing Northern and Southern garden art while maintaining its graceful and luxurious royal style. This enriched the content of the gardens and expanded the field of creativity. The gardens in “A Dream of Red Mansions” represent a fusion of Northern and Southern private gardens, imperial gardens (such as the villa built for visiting relatives), and folk culture, as seen in places like Daoxiang Village.

Based on the private gardens of the Qing Dynasty, they also incorporate many Manchu cultures and royal styles. In “A Dream of Red Mansions,” Cao Xueqin devoted himself to constructing many gardens, including the gardens of Jinling Ningguo Mansion and Rongguo Mansion, the Huifang Garden of the capital’s Ningguo Mansion, the garden of Rongguo Mansion, Daguan Garden, the garden of Jiangnan Zhen family, the garden of Shi Xiangyun’s family, and the garden of Lai Da’s family. Among them, Daguan Garden is undoubtedly the pinnacle of all gardens. Like traditional Chinese gardens, the gardens in “A Dream of Red Mansions” often center around a courtyard, with buildings surrounding it, forming a unique combination focused on external space. In landscape gardens, every scene speaks of emotion. The gardens in “A Dream of Red Mansions” are different from others. The people and events in the garden, as well as the joys and sorrows it holds, endow it with a soulful and elusive spirit. **Figure 1** illustrates the grand view of the garden floor plan in “A Dream of Red Mansions”.

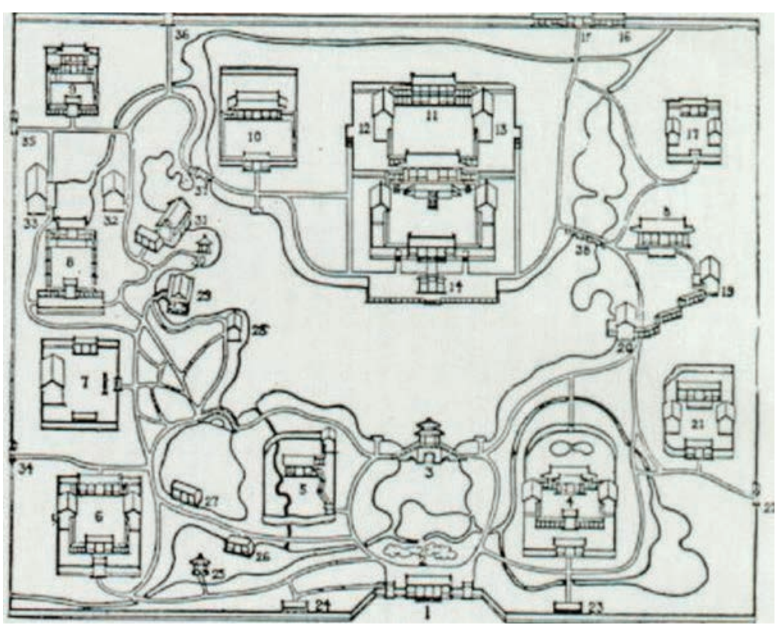


Figure 1. Grand view of garden floor plan

2. Changes in the garden and the destinies of characters in “A Dream of Red Mansions”

2.1. Contrast in creating the atmosphere of the Jia family’s rise and fall

The changes in the landscape of “A Dream of Red Mansions” are closely related to the fate of the family and its characters. The typical environments in the novel are the Rong and Ning mansions and Grand View Garden, which serve as the stage for hundreds of characters in the novel.

From the architectural layout of the Rong and Ning mansions to the furnishings of key halls and rooms; from the winding corridors and pathways within the courtyards to the scale and scenery of Grand View Garden; from the lush surroundings of Xiaoxiang Pavilion to the rustic charm of Daoxiang Village—every detail reflects the characteristics of its time, culture, and region, creating a distinct and representative environment. Every detail described in the work serves to enhance the authenticity of this typicality. In the first forty chapters of the novel, the Jia family is described as thriving, with an atmosphere of prosperity pervading both inside and outside the mansions. However, in the latter forty chapters, the Jia family begins to decline, with misfortunes piling up and various contradictions exposed. The gates of the Rong and Ning mansions become deserted, and Grand View Garden falls into desolation. Simultaneously, the typical living environment undergoes significant changes. This contrast creates two different atmospheres, reproducing the entire process of the Rong and Ning mansions’ rise and fall.

2.2. Tanchun’s prophecy on Grand View Garden foreshadows the rise and fall of the Jia family

The scene of prosperity reaches its peak during the visit of the noble consort. It is described that incense smoke curls upward in the garden, flowers are in full bloom, lights shine brightly everywhere, and soft music fills the air. This peaceful and prosperous scene is difficult to describe in words. However, prosperity is followed by decline. Although the outward appearance remains intact, the inner decay has already begun. The decline starts with the inspection and confiscation of Grand View Garden, as predicted by Tanchun: “Don’t worry, your turn for inspection will come! You woke up early today not to discuss the steamed bun seller, but to look forward to a good house search. Indeed, today is the day! Gradually, it will come to us too! You know, for such a large family, if attacked from the outside, it won’t be easily destroyed. This is what the ancients said, ‘A centipede dies but does not fall.’ It must first destroy itself from within before it can be completely ruined!”

2.3. Jia Yucun and Leng Zixing discuss the rise and fall of the Jia Family through the garden

In fact, these can be inferred from the dialogue between Jia Yucun and Leng Zixing at the beginning of the book. “Last year, when I went to Jinling, I wanted to visit the relics of the Six Dynasties. That day, when I entered the Stone City and passed by their old house, I saw that the street was divided by the Ning and Rong mansions. Although the gate was deserted, a glance through the fence revealed towering halls and pavilions. Even the trees and rocks in the garden behind still retained a lush and vibrant atmosphere. It didn’t look like a decaying family at all.” Leng Zixing laughed and said, “You’re a scholar, but you don’t understand! As the ancients said, ‘A centipede dies but does not fall.’ Although it’s not as prosperous as before, it’s still different from ordinary official families. Now, with the increasing population and expanding affairs, there are many who enjoy wealth and honor, but no one plans or strategizes. Their daily expenses cannot be reduced. Although the outer appearance remains intact, the inner decay has already begun. And there’s another important matter: who would have thought that in such a wealthy and educated family, the descendants would become worse with each generation!" [1].

2.4. The garden scenery after the decline of the Jia mansion

In "A Dream of Red Mansions", the garden serves as a vessel, accommodating the Hai Tang Society and its chrysanthemum poems, Dai Yu's Peach Blossom Society, and Xiang Yun's willow catkin poems. It embraces the melancholy flute melodies of Tu Bi Hall, the lonely poetry sessions of Ao Jing Hall, the crystal world of white snow and red plum blossoms, and the warm, improvised poems of Lu Xue Court. It holds all the joys, sorrows, rises, and falls within. However, in the end, even the tree marked with many rings of age can only timidly whisper, "Stay, stay, don't let the spring light fade away!" Yes, the spring light fades, families are broken, and from the descending pearl's soul returning to the world of regret, to the robbery of the wonderful jade within the threshold, from the exhaustion of Feng Jie's schemes to the end of Bao Yu's earthly ties, the Rong and Ning mansions are raided, the courtyard is deserted and desolate, and the seedlings are left untended, growing wildly. In Chapter 180, "Forced Laughter at Heng Wu's Birthday Celebration, Deathly Entanglement and the Weeping of Xiang Jiang," Bao Yu weeps uncontrollably for the deceased Dai Yu. The servants rush up and say, "Second Master, please go back quickly. It's already late. We dare to walk elsewhere, but this path is secluded, and we've heard that there are often crying sounds here after Miss Lin died, so no one dares to walk here." Is this the same Xiangxiang Pavilion where Jia Zheng once smiled and said, "If I could read under this window by moonlight, it would not be a wasted life"? Where have the once-elegant houses and thousands of green bamboos gone? The beauty is no more, only the weeping and wailing remain. Are those overgrown plants and trees, the empty courtyard after the raid, the flower shadows where one once lay drunk still there, and has the wooden boat rocking in the lotus pond already decayed? What about the calligraphy and paintings in the courtyard? The freely roaming ducks? Is the visitor under the banana leaves still strolling beneath them? Are butterflies still waiting for a fragrant fan to chase them? Even the garden's structure is gone; people and things are no longer the same. The scenery represents those people. With no people, for whom does the scenery maintain its beauty?

3. Classical Chinese garden landscaping techniques used in Daguanyuan

Classical Chinese gardens value the natural worship of harmony between nature and humanity, featuring a landscape type that imitates natural mountains and waters. Its poetic and artistic expression, clever use of borrowed scenery to expand the visual field, gradual spatial sequence, the visual effect of seeing the big in the small, and the subtle and implicit emotional expression create a comfortable and livable human environment, making classical Chinese gardens, especially private gardens, more charming and humane. The expression techniques commonly used in classical Chinese gardens include borrowed scenery, contrasting scenery, framed scenery, obstructed scenery, and accentuated scenery, all of which are manifested in the gardens of "A Dream of Red Mansions".

3.1. Borrowed view

The purpose of borrowed view is to expand the visual range of the garden and increase the landscape levels for garden appreciation. There are five ways of borrowed scenery: borrowing from a distance, borrowing from neighbors, borrowing by looking up, borrowing by looking down, and borrowing according to time and place [2]. The scene follows Jia Zheng and Baoyu as they walk through the garden, introducing the classical technique of borrowing by looking up and down. Upon entering a stone cave, they encounter a vivid composition: lush flowers and trees, delicate blossoms arranged with elegance, and a clear stream emerging from within the vegetation, dripping gently into the crevices of the rocks. This use of vertical borrowed view draws the gaze both upward to the foliage and downward to the flowing water, showcasing layered depth and a harmonious integration of natural elements. After a few more steps, they gradually moved northward, where the area became flat and open, with towering buildings on both sides hidden among the mountain ridges and treetops. Looking down from above, they saw only a jade-like stream flowing, stone steps piercing the air, white clouds serving as balustrades, surrounding a pond, with three bridges spanned by beast-headed spouts. There was a pavilion on the bridge, where Jia Zheng and the others sat. As for borrowing from a distance and neighbors, Bao Yu had a classic statement that nearly got him thrown out by Jia Zheng: "Here we go again! This place is clearly made by human hands: there is no neighboring village in the distance, it is not close to the city walls, there is no mountain range behind it, and no water source nearby. There is no temple tower looming above, and no bridge leading to the market below. It stands alone, seemingly unremarkable. It is not as impressive as the previous places, which had a natural reason and charm. Although bamboos are planted and a spring is drawn, it does not detract from the artificiality. The ancients said, 'natural picture,' but I fear that if it is not suitable for the location, it will not be harmonious, even if it is cleverly done." This also demonstrates the natural charm embodied in classical Chinese gardens, which draw essence from nature and reflect natural delight in the garden. Borrowing according to time refers to borrowing the rising sun in the morning, the setting sun in the evening, peach and willow trees in spring, lotus ponds in summer, maple leaves in autumn, and flying snow in winter [3]. Even the sounds of mountain springs and singing birds are borrowed [4]. This is very common in "A Dream of Red Mansions". Family members admire the moon in the Convex and Concave Crystal Pavilions, Jia Mu celebrates the flowering of the begonia, laughter floats from boats harvesting lotus in the pond, interesting things happen while admiring osmanthus and composing crab poems, couplets are recited while admiring snow in Lu Xue Court, feasts are held under the autumn wind in the tung tree, and spring water flows at Qin Fang Gate, among many other examples.

3.2. Opposite view

Opposite view refers to the formation of a scenic view between two points in a garden that have a clear line of sight. There are two types of opposite scenery: direct opposition and mutual opposition. Direct opposition is more commonly used in formal gardens, creating a sense of grandeur and solemnity. Mutual opposition, on the other hand, involves setting up scenery at both ends of an axis or predefined view, forming a pair of contrasting yet complementary views. This can be seen in the convex and concave pavilions in "A Dream of Red Mansions," as Xiangyun remarks, "Although the moon on this mountain is beautiful, it's not as wonderful as viewing the moon near the water. You know, the bottom of this hillside is the edge of the pond. The place near the water in the hollow of the mountain is called the Concave Crystal Pavilion. You can see that there was real scholarship in building this garden. The high point of the mountain is called Convex Jade, and the low point is called Concave Crystal. These two words, 'convex' and 'concave', have been rarely used by people in the past, but now they are used directly as the names of the pavilions, which makes them feel fresh and original. These two places, one high and one low, one bright and one dark, one tall and one short, one mountain and one water, were specially designed for enjoying the moon." This can be considered an example of mutual opposition, which is the main type of scenery used in "A Dream of Red Mansions".

3.3. Framed view

Framed view refers to the use of frames such as door frames, window frames, tree trunks, branches, or the openings of caves to selectively capture and frame views of another space, creating a scenic composition that resembles a picture embedded in a frame. As stated in "The Art of Landscape," "Using a white wall as paper and stones as the painting, planting Huangshan pine and cypress, ancient plum blossoms, and elegant bamboo, and framing them in the garden window creates a scene like wandering in a mirror." Window frames and door frames are common in everyday life, but let's look at a more unique example: "It was May, when the roses were in full bloom. Baoyu quietly peered through the fence and saw a girl squatting under the flowers, holding a hairpin in her hand and scraping the soil, while quietly weeping." "The girl was startled when she heard the voice, and she looked up to see a person outside the flowers telling her to stop writing. On the one hand, Baoyu's face was handsome, and on the other hand, the flowers and leaves were so dense that they hid most of his body, only revealing half of his face. The girl thought he was just another servant girl and didn't realize it was Baoyu. She smiled and said, 'Thank you, sister, for reminding me. Do you have something to protect yourself from the rain outside?" This illustrates the charm of framed scenery created by tree branches and flower branches.

3.4. Obstacle view

Obstacle view refers to barriers in a garden that block the view and guide spatial transformations. The role of obstacle scenery is to create anticipation and reveal scenery in a gradual manner, enriching the layers of garden landscape appreciation. The elements that constitute obstacle scenery can be buildings, rocks, plants, or small decorative features. Depending on the materials used, they can be classified as rock obstacles, screen wall obstacles, or tree cluster obstacles, etc. Chinese gardens are introverted, while Western gardens are extroverted. In Chinese traditional culture, even the most beautiful scenery is meant to be enjoyed with restraint, such as the screen wall in a quadrangle courtyard or the hidden sea in Hainan. The technique of obstacle scenery is frequently used in "A dream of Red Mansions". For example, when Jia Zheng, Baoyu, and the others visited the garden, they described: "They ordered the gate to be opened and saw a stretch of green barrier blocking their view. The guests exclaimed, "Beautiful mountain, beautiful mountain!" Jia Zheng said, "Without this mountain, all the scenery in the garden would be visible at once. Where would the interest be?" Another example is, "As they walked and talked, they suddenly saw a green mountain blocking their path. Turning around the mountain, they caught a glimpse of a yellow mud wall, covered with rice stalks. Hundreds of apricot blossoms were in full bloom, like a fiery blaze." Another instance is, "The courtyard was filled with roses. Turning past the flower barrier, they saw a clear stream blocking their way." and "Suddenly, a large mountain blocked their path, and everyone was lost. Following the others, they turned at the foot of the mountain and found a flat road leading to a gate that suddenly appeared before them." These are all examples of the use of obstacle scenery in the Grand View Garden. The arrangement of obstacle scenery creates a sense of movement and direction, with significant differences in the attractiveness of the scenery ahead.

3.5. Highlighted view

Highlighted view refers to capturing the characteristics of a landscape or the features of a spatial environment in a garden and summarizing them from a cultural and artistic perspective. It highlights the artistic conception of the scenery, enhances the artistic taste of the garden space, and enables visitors to have a deeper experience. In Chinese classical gardens, accent scenery includes naming scenery and inscribed poems or couplets about the garden. This is a very essential part of "A dream of Red Mansions". In the 17th and 18th chapters, there are detailed descriptions of accent scenery, such as the naming and inscribed poems for various scenes in the Grand View Garden. These reflect Baoyu's pure and beautiful disposition, as well as his soul's resonance with Daiyu's lonely and proud spirit.

4. Scholar gardens in "A Dream of Red Mansions"

Ancient Chinese scholars have always aspired to benefit the world when prosperous and to cultivate themselves when poor. Therefore, there has always been a tradition of scholar gardens in Chinese landscape architecture. Many scholars, who were also bureaucrats, not only participated in the development of scenery, greening, and beautification of the environment but also built their own private gardens. Relying on their deep understanding of natural scenery and their high appreciation of natural beauty, they managed their gardens, and at the same time, they integrated their experiences of life philosophy and feelings about official career ups and downs into the art of garden creation. The elegant and refined style of the scholar-bureaucrat gardens was further enhanced and sublimated, taking on a more scholarly hue. This gave rise to the "scholar garden", such as the Zhuozheng Garden, Ge Garden, Liu Garden, Wangshi Garden, and so on. The scholar garden is a type of garden that focuses more on pleasing the eye and the mind, expressing ideals, cultivating temperament, and embodying the reclusive spirit. By extension, it refers not only to gardens managed or owned by scholars but also to those gardens that have been "scholarized" by being infused with scholarly tastes. The Grand View Garden in "A Dream of Red Mansions" is a typical scholar garden, where every scene speaks of people, the beauty of the garden is colored, and the landscapes in the garden are related to the temperament and rest of the garden owner, and even secretly correspond to the fate of the garden's occupants.

4.1. Connection between garden landscapes and characters

The halls and courts in the Grand View Garden serve as residences for the characters, and their spatial arrangements and features subtly echo the characters' dispositions. For example, the "Place Where Phoenixes Come" was renamed "Xiaoxiang Pavilion" by Princess Yuan during her provincial visit. It is the residence of Daiyu, with pink walls, bamboo shades, and a quiet atmosphere created by winding corridors, a small courtyard, a stone path, pear blossoms, banana leaves, and a clear spring surrounding the garden. This perfectly matches Daiyu's lonely and noble character. The allusion of tears on mottled bamboo and pear blossoms with raindrops reflects Daiyu's extraordinary talent and her tendency to cry. Baoyu's couplet, "The smoke from the idle teacup in the tripod is still green, and the fingers are still cool after finishing a game of chess beside the secluded window," not only suggests the dense and deep bamboo but also hints at Daiyu's melancholy and sickly nature. On the other hand, the "Fragrant and Elegant Place" was renamed "Hengwu Court" by Princess Yuan and is the residence of Baochai. The court features a vast and winding pond, willows, peaches, and apricots shading the sky, cool tiled houses, water-ground brick walls, and a variety of fragrant and exotic plants [5]. Baoyu's couplet, "The talent that composes cardamom poems is still brilliant, and the dreams after a deep sleep are fragrant," along with the descriptions "talent is still brilliant" and "dreams are fragrant," perfectly matches Baochai's cold and elegant demeanor and talent.

4.2. Analyzing character traits through garden names

Naming gardens is a unique feature of Chinese landscaping, and in “A Dream of Red Mansions”, the garden names not only reflect the scenery but also serve as epithets for their owners. This can be seen in the poetic nicknames given to characters such as the Cheerful Red Prince, the Bamboo Forest Princess, and the Hengwu Jun. For instance, Daiyu, or the Bamboo Forest Princess, is often teased by Xiangyun about her love of crying, as reflected in the name of her garden, Xiangxiao Pavilion, which is associated with tears and feminine melancholy. This association adds a deeply personal and emotional dimension to the garden, making it a reflection of Daiyu’s character and life experiences.

The gardens in “A Dream of Red Mansions” are not just physical spaces but also extensions of the characters’ inner worlds. The contrast of red and green in Yihong Kuailv (a garden named after a poem by Du Fu, meaning “pleasing reds and lively greens”) reflects Baoyu’s mercurial personality, while the bright and lively scenery within mirrors his idealistic world.

The identities, personalities, and fates of the “Four Springs” in the novel and the layout of their gardens are particularly symbolic. Yuanchun, the noble and virtuous imperial concubine, lives in a magnificent villa that reflects her status and wealth. However, the grandeur and opulence are fleeting, and the emotional pain of separation from loved ones is a poignant reminder of the transience of worldly pleasures.

Jia Yingchun, the second daughter, leads a lonely life without the love of her parents, reflecting the neglect she faces in her family. Her garden, Zilingzhou (Purple Sandbar), seems to evoke a sense of pity and loneliness, mirroring her fate as a character who seems destined for sadness and isolation.

Qiushuang Studio, the residence of Tanchun, reflects her bright and capable personality. Her strong leadership and management skills are showcased in her governance of Daguan Garden, and her bold and decisive character is evident in her desire to make her own way in the world.

Xichun, the youngest of the Four Springs, withdraws from the world, finding solace in the solitude of her garden, Warm Fragrance Valley. Her cold and detached demeanor reflects her disgust with the secular world, culminating in her decision to retreat into a Buddhist life, seeking peace and tranquility away from the turmoil of her family.

In conclusion, Cao Xueqin intricately links the gardens in “A Dream of Red Mansions” to the characters’ personalities and fates. The carved balustrades and jade-like waves reflect not only the beauty of the gardens but also the joys and sorrows of the people within, shining with the dazzling brilliance of humanity that will never fade.

“When falsehood is taken as truth, truth becomes falsehood; where there is nothing, there may be something, and vice versa.” The gardens in “A Dream of Red Mansions” resemble the Illusory Land of Great Void in Baoyu’s dream, shrouded in mist and suspended between fantasy and reality. Names such as “Thousand Reds in One Grotto” and “Ten Thousand Beauties Share Sorrow” evoke deep emotional undercurrents, reflecting hidden joys and sorrows. These carefully crafted scenes stir the heart with their shifting moods and quiet intensity. Melancholy melodies drift through the air, as emotions rise and fall, and unspoken grief quietly takes hold.

And yet, amidst this blur of fantasy and reality, the gardens in “A Dream of Red Mansions” remain vibrant with the spirit of spring. Every year, new branches sprout green, flower buds unfurl, and northern geese return to the south, accompanied by the serene moonlight reflecting on the rippling waves. Year after year, joy and laughter, bickering and playfulness continue without end. The crane’s shadow on the cold pond and the poetic soul beneath the lonely moon drift into dreams, accompanied by the unforgettable flute songs from the lotus-gathering boats.

5. Conclusion

The pursuit of artistic conception is a distinctive feature of Chinese classical gardens. In his book "Renjian Cihua" (Notes on Poetry), Wang Guowei argues that "landscape is not merely about scenery; joy, anger, sorrow, and happiness are also aspects of the human heart's realm. Therefore, those who can depict true scenery and true emotions are considered to have attained a realm. Otherwise, they are considered to have no realm." Because of the Chinese tradition of scholars building gardens, Chinese gardens can be seen as a symbiotic and synchronous development of landscape painting and pastoral poetry, both of which have emphasized spiritual contemplation and charm since their inception. Chinese traditional gardens always mention homes and gardens together, implying that where there is a home, there must be a garden. Recently, there has also been great emphasis on environmental design abroad, indicating that external spatial environments, as extensions and complements of indoor spaces, are also indispensable. The difference lies in the fact that abroad, buildings are often the center, surrounded by gardens, while in China, the tradition is often the opposite, with gardens as the center and buildings surrounding them. Both inward- and outward-facing gardens have their respective advantages. The traditional Chinese garden techniques of borrowing scenery, framing scenery, blocking scenery, and highlighting scenery share remarkable similarities with modern landscape design techniques such as undulation and layering, spatial contrast, seeing and being seen, concealing and revealing, emptiness and solidity, primary and secondary focus, sparsity and density, guidance and suggestion, winding paths and varying heights, looking up and looking down, permeability and hierarchy. Modern landscape design should explore traditional gardens, learn from the past, innovate while carrying forward the essence of traditional Chinese gardens.

Disclosure statement

The author declares no conflict of interest.

References

[1] Cao X, Gao E, 1982, Dream of the Red Mansions. People's Literature Publishing House, China.

[2] Chongqing Landscape Architecture Society, 2007, Landscape Planning and Design. China Architecture & Building Press, China.

[3] Zhou W, 1999, The History of Chinese Classical Gardens. Tsinghua University Press.

[4] Ji C, 1998, The Craft of Gardens: A Commentary and Annotated Translation of "Yuan Ye". Jilin Literature and History Publishing House, China.

[5] Guo T, 2014, An Exploration of the Garden Art of Daguan Garden in "Dream of the Red Mansions", thesis, Xi'an University of Architecture and Technology.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Design and Finite Element Analysis of Smart Lining Trolley for Plateau Railway

Yuan Wang*

HanJiang Heavy Industry Co., Ltd. of CR11G, Xiangyang 441006, Hubei, China

Author to whom correspondence should be addressed.

Abstract: As a key national project, a newly built plateau railway features a large proportion of tunnels and high construction difficulty. To reduce the voids in the secondary lining of tunnels and address issues such as ineffective vibration of the vault, vault voiding, and the inability to monitor the casting status during tunnel lining construction with ordinary lining trolleys, a new smart lining trolley with large clearance that integrates functions such as vibration, automatic casting, and pressure monitoring has been developed. This was achieved by combining the functional design of the new smart lining trolley, comparing traditional construction techniques, and introducing information-based and intelligent design concepts. Through simulation calculations using finite element software modeling, it is verified that the structural stiffness, strength, and other performance parameters of the smart lining trolley meet the technical design requirements.

Keywords: New lining trolley; Smart casting; Finite element; Informatization

Online publication: July 1, 2025

1. Introduction

Constructing a plateau railway in our southwestern region requires overcoming a series of world-class challenges, such as alpine hypoxia, permafrost, and ecological fragility [1, 2]. The railway construction process spans across China's first and second terrain steps, with extreme topographical differences along the route. Bridges and tunnels account for over 90% of the route, and the total tunnel length exceeds 1,200km [3, 4]. Tunnel construction greatly affects the overall construction quality and progress.

The construction of the plateau railway faces numerous challenges along the route, such as high altitude, cold climate, and intense geological activity, making the construction difficult and posing high safety risks. This places higher demands on the quality of tunnel construction. As an essential part of tunnel construction, the secondary lining pouring process directly impacts the tunnel's safety. Traditional secondary lining pouring techniques, which use regular secondary lining trolleys, make the pouring process difficult to observe and vibrate, easily leading to defects such as voids, insufficient thickness, and cracks in the arch, affecting the tunnel's engineering quality.

As a national key and difficult project, the plateau railway needs to change traditional tunnel construction techniques and design a new type of smart trolley to address the aforementioned tunnel defects, achieving mechanization, informatization, and intelligence in tunnel construction [5, 6].

Based on the requirements of plateau railway tunnel construction, this paper has developed a new smart trolley that integrates an automatic pouring and distribution system, a vibrating system, an arch void monitoring system, and a concrete flow and temperature detection system. This trolley enables visualization, informatization, and intelligence in the secondary lining concrete pouring process, reducing the labor intensity of the secondary lining team and improving the safety and quality of tunnel construction.

2. Scheme design and key technologies

2.1. Structural design

When using a secondary lining trolley for concrete pouring, the trolley mainly bears the vertical pressure of the concrete, as well as the lateral pressure from both sides of the concrete. Traditional secondary lining trolleys use a multi-truss structure to withstand concrete pressure from different directions, making the truss structure bulky and occupying passage space. The new smart trolley sets long screws between the side formwork and the arch, transferring the concrete pressure from the side formwork to the crossbeam of the arch through the long screws. The arch becomes the main structure bearing the lateral force, while the vertical concrete pressure on the top formwork is transferred to the supporting screws under the side formwork through screws and templates. Ideally, the truss is not subjected to external loads during secondary lining concrete pouring. It only carries the templates and arches when the trolley moves to the next secondary lining pouring position. Therefore, the truss structure can be lightened through lightweight design, adopting a two-end supported truss structure, reducing the number of trusses, and increasing the clearance height and width for vehicles passing under the trolley.

The overall scheme of the new smart trolley is shown in **Figure 1**, and the main performance parameters are listed in **Table 1**.

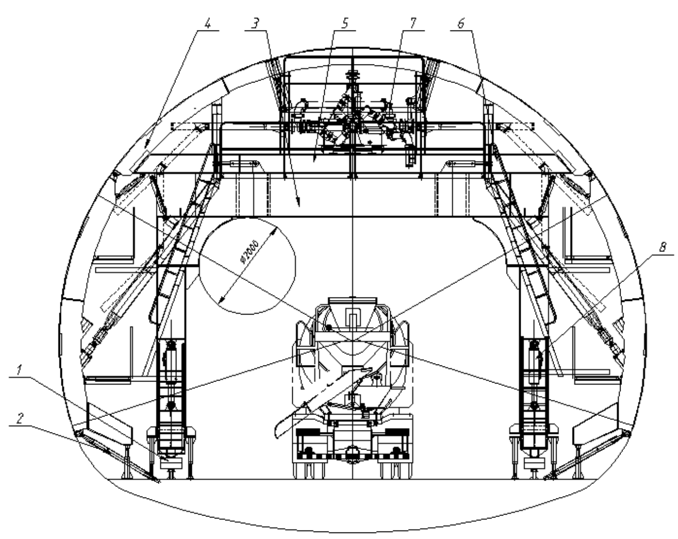


Figure 1. Overall scheme diagram of intelligent trolley for plateau railway, (1) Running mechanism; (2) Screw rod; (3) Portal frame; (4) Template assembly; (5) Arch frame; (6) Accessory platform; (7) Automatic pouring system; (8) Hydraulic and electrical system

Table 1. Performance parameters of intelligent trolley for plateau railway

No.	Parameter name	Parameter value
1	Jumbo Panel Thickness */mm*	14
2	Travel Speed *m/min*	5
3	Drive Motor Power */KW*	2 × 7.5
4	Hydraulic Motor Power */KW*	1 × 7.5
5	Jacking Cylinder Stroke */mm*	400
6	Side Cylinder Stroke*/mm*	360
7	Traverse Cylinder Stroke*/mm*	±150
8	Single Pour Lining Length*/m*	12
9	Jumbo Type	Hydraulic self-propelled
10	Travel Mode	Rail self-propelled

During concrete pouring, the portal frame of the trolley is in a suspended state, relying mainly on the template and the upper arch frame to bear the lateral and top concrete loads.

The template, as a component directly contacting the secondary lining concrete, its stiffness and manufacturing level are directly related to the quality of the tunnel secondary lining construction. The plateau railway faces a large number of long and difficult tunnels. To ensure sufficient stiffness and durability of the template, the panel adopts 14mm steel plate, the waist plate adopts 12mm steel plate, the arch template is strengthened with 14a channel steel, and the side template is strengthened with L110 × 70 × 6 unequal angle steel, with a spacing of 260mm. In the manufacturing process, reasonable processing and welding processes are adopted to ensure high accuracy of the template's external quality and dimensions. Specialized assembly welding jigs are designed and processed to effectively ensure the accuracy of the overall dimensions, with small welding deformation, smooth outer surface, and no concave-convex defects. The connecting plates of adjacent templates are fixed into one unit by using interference-fit stabilizing pins, effectively controlling the problem of misalignment between adjacent templates and ensuring the quality of concrete lining.

Through structural design, the trolley can accomplish the following functions:

(1) When the trolley deviates from the centerline during travel or when constructing curved tunnels, it can be adjusted through the trolley's transverse shifting mechanism to meet design and construction requirements.

(2) The trolley has sufficient strength and stiffness. Under the combined action of hydraulic cylinders and supporting screw rods, it can resist vertical and lateral pressures from the concrete, with minimal deformation that does not affect the quality of the poured concrete.

(3) Each steel formwork joint is tight, the concrete is dense, and there are no honeycomb, spot, or misalignment defects. The surface is smooth, flat, and aesthetically pleasing.

2.2. Information system design

The information system of the new intelligent trolley mainly includes functions such as a vibrating system, concrete pouring and distribution system, arch void monitoring system, and formwork grouting system. Through the information system settings, visualization, informatization, and intelligence during the secondary lining pouring process are achieved, improving construction efficiency and tunnel lining construction quality [7–12].

2.2.1. Vibrating system

The tunnel lining trolley's vibrating design utilizes a combination of electric insert-type vibrators and pneumatic attached vibrators. Pneumatic vibrators have ultra-high vibration frequencies, with amplitudes that are one-third of electric vibrators with the same vibrating performance. Simultaneously, the frequency exceeds the natural resonance frequency of the template, reducing damage to the template.

The fully automatic insert-type high-frequency vibrating device consists of insert-type vibrators, control circuits, and a control system. The insert-type vibrators are installed in blind spots for manual vibration and weak positions for secondary lining pouring. Utilizing the fully automatic high-frequency insert-type vibrator achieves vibration of the arch lining concrete, compensating for the lack of vibration in the arch top lining concrete and effectively addressing issues such as uneven strength, incompactness, and voids in the arch top concrete.

The arch vibration adopts a combination of insert-type vibration and pneumatic vibration. The trolley is equipped with 4 sets of insert-type vibrators and 24 sets of pneumatic vibrators.

2.2.2. Automatic pouring and distribution system

To achieve fast, stable, and continuous concrete pouring, the smart lining trolley employs a pressurized pouring system. Traditional chutes are replaced with adjustable telescopic delivery pipes and rubber sealing devices, enabling pressurized concrete pouring and significantly addressing lining construction challenges such as inadequate arch top concrete pouring. The automatic distribution system (**Figure 2**) utilizes a distribution trolley connected to both sides of the pipeline, achieving symmetrical pouring on the left and right. By blocking one side of the pipeline, arch top pouring can be achieved.

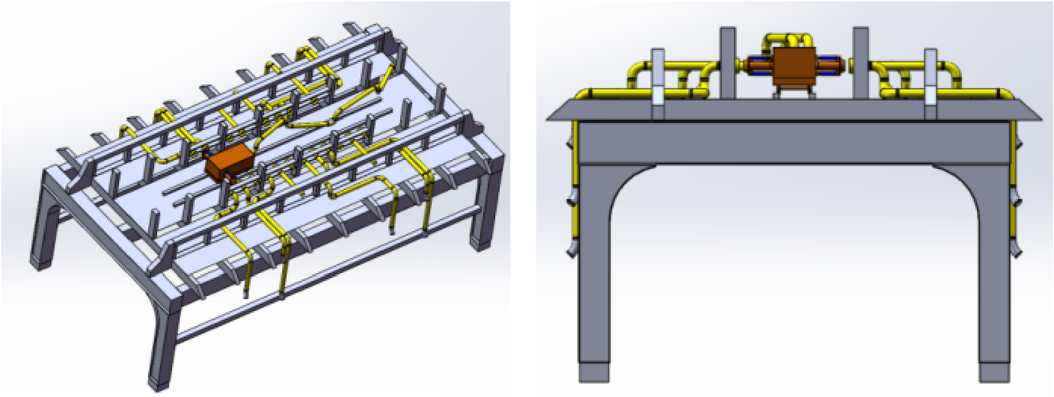


Figure 2. Automatic pouring and distribution system with translation and docking of distribution trolley

This distribution system is simple to operate, reduces labor intensity for workers, has high construction efficiency, and short pouring intervals, which is beneficial for improving the quality of tunnel secondary lining construction.

2.2.3. Arch void prevention monitoring system

This system consists of a warning control box, electrode connecting wires, detection electrodes, and an information processing system. The RPC tube serves as the carrier for the detection electrode, which does not need to be attached to the waterproof board and can be reused.

Pressure sensors are installed at the arch position of the trolley. When concrete is poured to the location of the pressure sensor, it outputs a signal. As the thickness of the arch concrete changes, the system displays the real-time concrete pressure value at the arch of the trolley. When the displayed arch pressure value exceeds the set pressure value in the system, the trolley system emits an alarm indication, showing that the concrete pouring is in place.

2.2.4. Flow and temperature monitoring system

Concrete flow sensor wires and temperature measurement devices are installed in the concrete pouring pipeline to record the volume and inlet temperature of poured concrete accurately in real-time. The project department can monitor and control the concrete pouring process from outside the tunnel.

3. Finite element calculation

3.1. Calculation of mechanical parameters

The effective lining length of the smart trolley is 12m, and the thickness of the formwork panel is 14mm. The strength and stiffness of the main stressed components of the trolley are checked to verify whether the mechanical properties of the trolley can meet the operating requirements.

Calculation of the pressure exerted by concrete on the top form. The pressure on the top form is mainly lateral pressure, and the effective head height is calculated as shown in Formula (1).

$$h = 1.53 + 3.8\ v/T \tag{1}$$

The maximum lateral pressure exerted by the concrete on the top form is calculated as shown in Formula (2).

$$P_1 = \gamma h \tag{2}$$

In the formula: P_1 - the maximum lateral pressure exerted by the freshly poured concrete on the top form; γ - the bulk density of concrete (kN/m^3), where γ =24 kN/m^3; T - the temperature of the concrete when poured into the form (°C), where T=20°C; v - the pouring speed of concrete (m/h). Due to the smaller arc slope during top form pouring, the pouring speed is taken as 1m/h, and the pouring speed of concrete is taken as 2m/h when calculating the side form.

According to Formula (2), the maximum lateral pressure exerted by concrete on the top form is calculated as P_1=41.28 kN/m^2.

The pressure exerted by concrete on the side form is shown in Formula (3).

$$P_2 = 0.2\ \gamma T \beta_1 \beta_2 v^{1/2} \tag{3}$$

In the formula: P_2 - the lateral pressure exerted by freshly poured concrete on the side form; β_1 - the correction coefficient for the influence of admixtures, take 1.0 when no admixture is added, and 1.2 when adding a retarder admixture, considering the influence of admixtures during calculation; β_2- the correction coefficient for the influence of concrete slump speed, when the slump is less than 30mm, take 0.85; 50–90mm, take 1.0; 110–150mm, take 1.15, calculated according to 1.15; When calculating the side form load, the impact load P_3 generated by dumping concrete should also be considered, taking P_3 = 4 kN/m^2.

The maximum lateral pressure on the side form of the trolley during pouring is calculated as follows:

$$P_4 = P_2 + P_3 \tag{4}$$

According to Formula (4), the maximum lateral pressure on the side form during pouring is calculated as $P_4 = 64.4\ kN/m^2$.

The calculated load is applied to the corresponding top and side forms as a uniformly distributed pressure.

3.2. Analysis of simulation calculation results

Figure 3 represents the finite element model of the trolley under working conditions, with a maximum stress of 168 MPa and a maximum deformation of 4.9 mm.

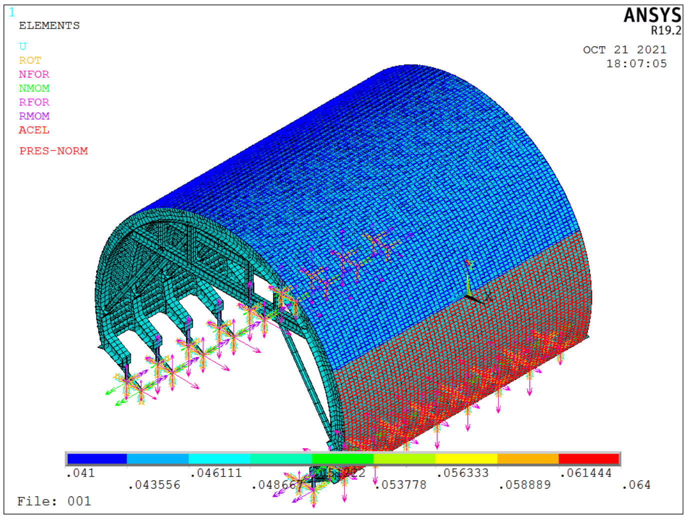


Figure 3. Constraints and loading conditions of lining trolley

The finite element calculation results of the trolley are shown in **Figure 4** and **Figure 5**.

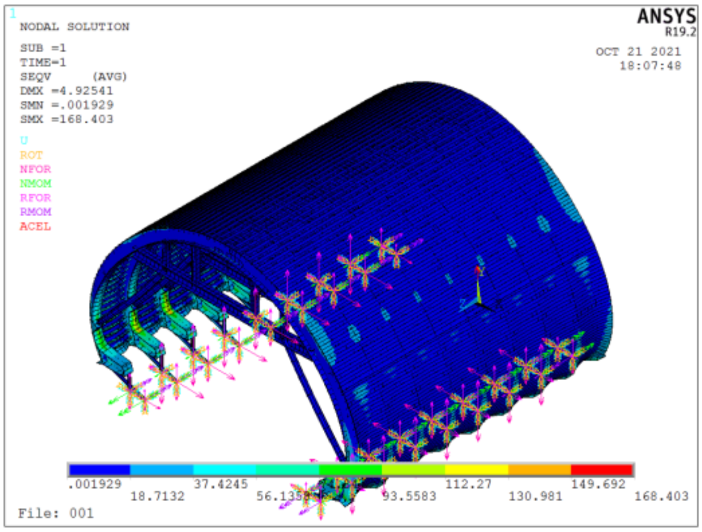


Figure 4. Calculation results of stress in the working state of the lining trolley

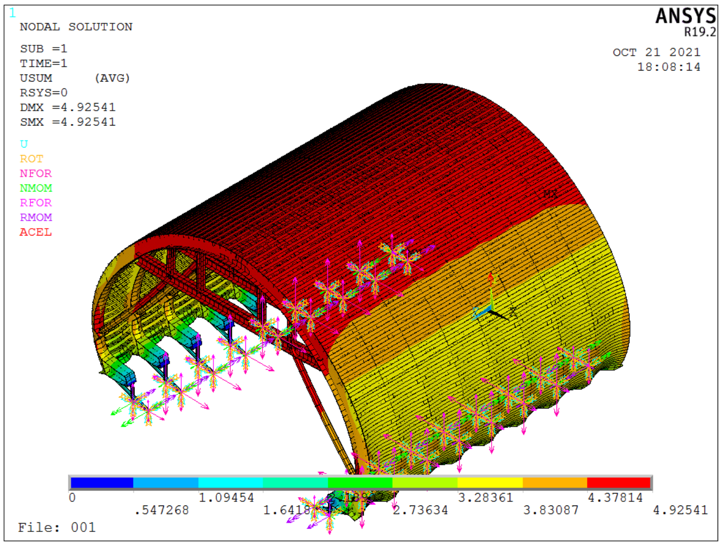


Figure 5. Calculation results of overall machine deformation

Figure 6 illustrates the stress distribution of the gantry under transportation conditions, with a maximum stress of 80 MPa.

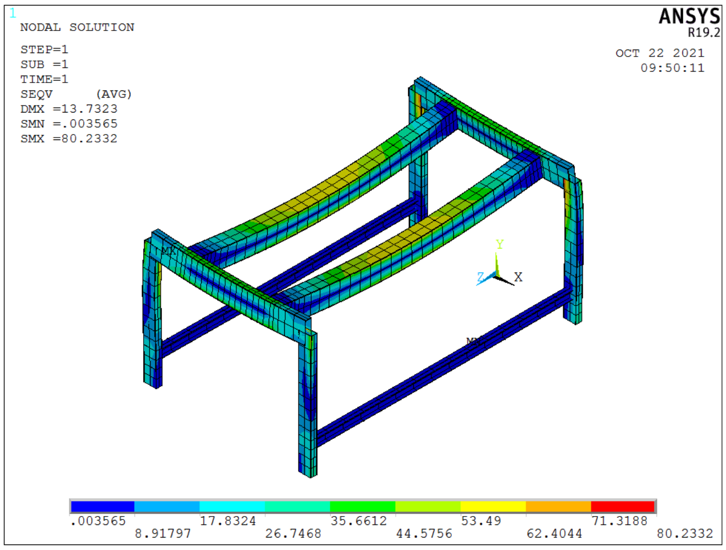


Figure 6. Calculation results of gantry stress

The main structural steel of the trolley is Q235B carbon structural steel, with a gravity density of 78.5 and an elastic modulus of 206 GPa. Referring to the "Standard for Design of Steel Structures" (GB5017-2017), when the thickness of Q235B steel plate is between 16 mm and 40 mm, the structural strength safety factor is taken as 1.25, and the allowable stress [σ] is 188 MPa. The finite element calculation results indicate that the maximum stress of the trolley under working conditions is 168 MPa, which is less than the allowable stress, demonstrating that the strength meets the design requirements.

The concrete pressure on the trolley is set based on the maximum condition, and the force models used in the above mechanical analysis process are calculated using simplified methods that yield results biased towards safety. This article analyzes the main stressed components and vulnerable parts of the trolley. Through the above analysis, each component can meet the stress requirements and can satisfy the stress demands of on-site construction.

4. Conclusion

The newly developed smart trolley has been successfully implemented in newly constructed plateau railway projects. Field application results indicate that the secondary lining concrete is dense, of high quality, and features a smooth, visually appealing surface. The trolley's design optimizes the traditional structure by transferring the main load to the formwork and upper arch frame, which reduces the gantry's weight and increases the clearance beneath the trolley. Finite element analysis software was used to simulate and calculate the structural performance, confirming that all components meet the required stress conditions. Additionally, the integration of a concrete vibrating system and an automatic pouring and distribution system enhances the density and quality of the secondary lining concrete, while minimizing defects during later stages of use. Advanced functions such as arch top void prevention detection, flow monitoring, and temperature monitoring enable real-time visualization of the concrete pouring process. This allows the project team to monitor conditions continuously and make timely adjustments based on feedback from the information system, thereby improving the overall level of project management.

Disclosure statement

The author declares no conflict of interest.

References

[1] Zhang J, Tang Q, Zhang Z, Ma H, 2021, Safety Risk Evaluation of Tunnel Construction in the Yalin Section of the Plateau Railway. Journal of Safety and Environment, 21(125): 1873–1879.

[2] Xue Y, Kong F, Yang W, et al., 2020, Main Unfavorable Geological Conditions and Engineering Geological Problems Along the Plateau Railway. Chinese Journal of Rock Mechanics and Engineering, 39(364): 445–468.

[3] Zhang J, Xu J, 2020, Safety Risk Evaluation of Bridge and Tunnel Construction on the Plateau Railway. Journal of Safety and Environment, 20(115): 39–46.

[4] Zheng Z, Sun Q, 2017, Tunnel Engineering of Plateau Railway. Tunnel Construction, 37(205): 1049–1054.

[5] Hu F, 2020, Design and Application of Double-Span Large-Space Intelligent Lining Trolley. Construction Machinery, 41(375): 46–49.

[6] Wang B, 2019, Research and Application of Automatic Control System for New Intelligent Lining Trolley Construction. Tunnel Construction (Chinese and English), 39(231): 1728–1735.

[7] Jiang J, Guo B, Lin Y, 2019, Research on Construction Technology of Automatic Distribution and Pressure Casting Intelligent Lining Trolley. Railway Construction Technology, 307(2): 18–23.

[8] Ji H, Liu Z, Zhang H, 2018, Research and Application of a New Digital Lining Trolley for Pressure Casting Tunnels. Tunnel Construction, 38(8): 1384–1390.

[9] Zhang H, 2017, Application of Tunnel Lining Layer-by-Layer and Window-by-Window Casting and Formwork Grouting Technology. Tunnel Construction (Chinese and English), 37(12): 6.

[10] Zhang X, Zhang H, He Y, 2017, Optimization of Construction Technology for New Railway Tunnel Lining Trolley with Formwork Grouting. Railway Construction, 2017(5): 3.

[11] Yu Z, 2017, Research on Fast Positioning System of Tunnel Lining Trolley. Science and Technology Information, 15(5): 2.

[12] Liang S, 2017, Research and Application of Lightweight Tunnel Lining Trolley, thesis, Kunming: Kunming University of Science and Technology.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Real-time Monitoring and Alarm Strategy for Construction Site Safety Based on the Integration of BIM and AI

Ying Peng, Huiming Qin, Lianyuan Peng, Taolin Luo, Baoming Dai, SiyanYu, Yifei Xu

Chongqing Institute of Engineering, Chongqing 400056

Abstract: Combining the background of modern construction engineering site safety management, this article analyzes the real-time monitoring and alarm strategies for site construction safety under the integration of BIM and AI. This includes the analysis of BIM and AI technologies and their integration advantages, real-time monitoring and alarm strategies for construction site safety based on BIM and AI integration, as well as the development direction of BIM and AI integration in real-time monitoring and alarm for construction site safety. It is hoped that through this analysis, a scientific reference can be provided for the digital and intelligent management of construction site safety, promoting the digital and intelligent development of its safety management work.

Keywords: BIM technology; AI technology; Construction safety; Real-time monitoring; Risk warning

Online publication: July 1, 2025

1. Introduction

BIM and AI technologies play significant roles in modern construction site safety supervision. Therefore, the integration of BIM and AI technologies has become a key focus in the field of construction safety management. To achieve a reasonable integration of the two technologies, researchers should first fully understand their basic conditions and integration advantages. Then, according to the actual safety management requirements in construction projects, they should install high-definition cameras, sensors, and other equipment in appropriate areas of the site, transmit monitoring data to the BIM model in real-time, and intelligently process and analyze the safety monitoring data under the BIM model conditions through reasonable safety warning mechanism grading settings and AI data analysis. This will facilitate the timely detection of potential safety hazards and issuance of early warnings. The main integration feature is to achieve clear and stable monitoring image capture, conduct safety control of the entire construction process, and realize the visual display of safety warning information with the support of the BIM model, thus providing technical support for real-time monitoring and early warning of construction safety.

2. BIM, AI, and their integration advantages

2.1. BIM technology

BIM (Building Information Modeling) is a technology that implements digital 3D modeling of construction projects supported by digital technology. Through the comprehensive integration of various building information, a three-dimensional model consistent with the actual construction project can be constructed in the supporting software to achieve comprehensive sharing of building information and provide support for construction engineering design, construction, and operation and maintenance work. With advantages such as three-dimensional visualization, data integration, collaboration, simulation, and lifecycle management, BIM technology has been widely used in current construction engineering planning, design, construction, operation, and maintenance management fields [1].

2.2. AI technology

AI (Artificial Intelligence) is an emerging technology that simulates, extends, and expands human intelligence technologies, methods, and theories. The core goal of this technology is to make machines think, learn, and solve problems like humans, and even surpass human thinking and behavioral abilities in some aspects. In terms of current AI technology, its key components include machine learning technology, deep learning technology, natural language processing technology, computer vision technology, and robotics technology. With powerful advantages in large-scale data learning and processing, parallel computing and logical reasoning, multi-modal fusion and perception, AI technology has been widely used in current medical, manufacturing, construction, transportation, education, entertainment, and other fields.

2.3. Advantages of BIM and AI integration

In modern construction site safety management, the integration of BIM and AI technologies can exhibit several advantages. Firstly, using the BIM model as a carrier, real-time data collection through IoT sensors, cameras, and other devices, combined with AI algorithms for spatiotemporal analysis, enables the organic integration of multi-source data. This further enhances the efficiency and quality of monitoring data processing, allowing timely and accurate identification of various safety risks. Secondly, mapping the on-site safety hazard information identified by AI into the BIM model and displaying it in a three-dimensional visual manner can help managers quickly locate and address issues [2]. Finally, the AI model can dynamically adjust on-site construction safety monitoring strategies based on construction progress and environmental changes, while the BIM model can be synchronously updated according to the adjustments of the AI model, ensuring the real-time and adaptability of safety management work.

3. Analysis of real-time monitoring and alarm strategies for construction site safety based on BIM and AI integration

For modern construction site safety supervision, real-time safety monitoring and early warning are crucial in high-risk areas such as deep foundation pits and high-rise formwork [3]. To ensure the safety of construction projects, researchers can integrate advanced BIM and AI technologies into this management work, focusing on high-risk areas as key monitoring zones. The following strategies can be employed for real-time monitoring and early warning:

3.1. Basic integration approach analysis

In real-time monitoring and alarm systems for construction site safety, BIM and AI technologies should be integrated through the construction of such systems. Typically, the overall architecture of the system should consist of four levels: the perception layer, the edge layer, the platform layer, and the application layer [4]. With the support of this system, the integration strategy of BIM and AI technologies is as follows:

(1) Utilize the perception layer to collect real-time data on site personnel behavior, equipment status, and environmental parameters.

(2) Utilize the edge layer to process and analyze the collected on-site data in real-time, reducing the computational pressure on the platform layer.

(3) Utilize the platform layer to integrate and process multi-source data, identifying and evaluating safety risks in on-site construction through feature extraction.

(4) Utilize the application layer to provide real-time hazard alarms, track disposal processes, and support multi-terminal access.

Table 1 shows the basic composition of the real-time monitoring and alarm system for construction site safety.

Table 1. Basic composition of real-time monitoring and alarm system for construction site safety

No.	Layer	Components
1	Perception layer	Cameras, pressure sensors, millimeter-wave radar, etc.
2	Edge layer	Edge intelligent gateway
3	Platform layer	Edge intelligent gateway
4	Application layer	Edge intelligent gateway

3.2. Analysis of real-time monitoring technical solutions

In the real-time monitoring and early warning system for construction site safety based on BIM and AI technology, the main solutions for real-time monitoring technology are as follows.

The first step is data acquisition. High-definition cameras and AR (Augmented Reality) eagle-eye devices are reasonably deployed to the construction site to ensure comprehensive coverage of the entire construction site. The equipment layout density in high-risk areas for safety accidents, including deep foundation pit construction areas and high-support formwork construction areas, is strengthened to ensure comprehensive and dead-angle-free monitoring. This enables real-time collection of monitoring data in high-risk areas, and the use of AI algorithms to analyze video streams for timely and accurate identification of various safety violations. With the help of advanced smart sensor equipment, real-time data collection is carried out on site deep foundation pit slope displacement, high-support formwork system wind load, and other data. Combined with the BIM model, real-time evaluation of its status is carried out to achieve good effects such as automatic driving and obstacle avoidance [5]. Through temperature and humidity, noise, and other sensor equipment, real-time monitoring of site environmental parameters is carried out, and combined with the BIM model, scientific analysis of the safety impact of the construction environment is carried out [6].

Second step is data fusion and processing. The data obtained by the sensors are imported into the BIM model and matched with the three-dimensional coordinates to ensure the consistency of the data in time and space. With the help of machine learning and filtering algorithms, noise reduction processing is performed on the initial monitoring data obtained. Then, with the help of isolated forests, long and short-term memory network algorithms, etc., corresponding abnormal behavior models are established to achieve real-time detection of abnormal data points.

Finally, the next step is edge computing and intelligent analysis. Deploy edge gateways in lightweight AI models to enable real-time, dynamic analysis and initial screening of video streams, further reducing the amount of data transmission during system operation and preventing information congestion. In the collaborative work mode of edge devices and cloud servers, complex tasks are processed through the cloud, and simple tasks are completed through edge computing, significantly improving the overall system's safety monitoring efficiency.

3.3. Analysis of safety warning and disposal process

In the real-time monitoring and early warning system for construction site safety based on BIM and AI technology, to ensure the rationality of the safety warning and disposal process, researchers need to reasonably determine the safety warning and disposal process through methods such as graded warning mechanism settings and closed-loop disposal management.

The first is to set up a graded warning mechanism. In this process, researchers can divide the warning mechanism into three levels according to the actual situation on site and construction safety monitoring requirements. The setting method is to establish a safety risk database in the system, which comprehensively covers the existing types of construction site safety risks and related data, and sets the threshold for each warning level according to the construction site safety management requirements. Supported by BIM and AI, through the comprehensive integration of historical safety hazard data, on-site video streams, and sensor monitoring data, as well as the comparison of relevant data and thresholds, the warning level is determined, and corresponding warnings are issued in a timely manner. **Table 2** shows the graded setting of the construction site safety warning mechanism based on BIM and AI technology.

Table 2. Classification settings of construction site safety early warning mechanism based on BIM and AI technologies

No.	Alert level	Objectives & methods	Alert response
1	Level 1 alert	Identify violations using AI algorithms	Immediately trigger audible and visual alarms; notify management personnel
2	Level 2 alert	Identify high-risk areas using historical data and BIM models	Immediately activate audible and visual alarms; notify management; guide personnel evacuation from hazardous areas
3	Level 3 alert	Detect equipment status/operational parameter anomalies via BIM models and AI algorithms	Automatically initiate equipment shutdown; immediately activate emergency response plan

The second aspect is closed-loop management of safety risks. For safety hazards identified on the construction site, the system immediately maps the information to the BIM model, showing managers the location and detailed information of the hazards through three-dimensional visualization. Supported by AI algorithms, the system automatically generates reasonable rectification tasks based on the actual situation and pushes them to managers via a user-end APP, requiring them to complete the disposal of safety hazards within a limited time. Meanwhile, the system can also monitor the rectification process of safety hazards in real-time through devices such as cameras and sensors set up on site and provide reasonable rectification suggestions based on the actual situation [7]. After the rectification is completed and the elimination of safety hazards is confirmed, the system will automatically update the BIM model status. This forms a closed-loop management mode that combines early warning, disposal, and verification, providing informatization and intelligent technical support for construction site safety risk management.

3.4. Analysis of key points for technology integration implementation

In real-time monitoring and early warning management of construction site safety, researchers should pay attention to the following aspects to achieve effective integration of BIM and AI technologies.

Firstly, lightweight processing should be implemented for the BIM model. The BIM model should be stored in IFC format, and technologies such as AI-based semantic simplification and geometric compression should be used to reduce model complexity and improve loading speed. Additionally, the WebGL plug-in should be used to process the BIM model, enabling visual display in the browser and supporting multi-terminal access.

Secondly, reasonable optimization of the AI model is essential. This includes expanding the AI model training dataset through methods such as adding noise and rotating or scaling images to improve its generalization ability. Techniques such as pruning and knowledge distillation can be used to reasonably compress the AI model to adapt it to the computing resources of edge devices. Regularly updating training data and optimizing the AI model through transfer learning can enhance its adaptability to dynamic changes on the construction site.

Finally, rational design of the network architecture is crucial. Advanced 5G mobile network technology should be introduced to meet the high-speed data transmission requirements of the system. Additionally, Mesh networking can be used to eliminate signal dead zones within the monitoring range, ensuring stable transmission of all monitoring data and control commands [8].

4. Development directions for the integration of BIM and AI in real-time monitoring and alarming of construction site safety

With the continuous development of modern construction management techniques, BIM and AI technologies applied in real-time monitoring and early warning of construction site safety should also be further innovated. To achieve better integration application effects, researchers can identify the following two integration development directions.

4.1. Deep optimization of algorithms and models

To meet the needs of real-time monitoring and alarming for modern construction site safety, researchers can open up new integration development directions through deep optimization of algorithms and models in the integration process of BIM and AI technologies. Firstly, researchers can construct a corresponding construction safety behavior recognition model in the fusion system through multi-source data fusion, such as language, vision, and touch, to achieve three-dimensional reconstruction of the posture of construction workers on site, thus timely detecting their safety violations. Secondly, researchers can introduce advanced reinforcement learning technology into the system to provide support for the independent optimization of construction safety real-time monitoring strategies under AI model conditions, adapting to different safety control requirements in different construction stages. Finally, under the condition of ensuring data security, researchers can introduce relevant data from multiple similar construction projects to train the AI model through federated learning, further improving the universality of the AI model and providing more powerful intelligent algorithm model support for on-site construction safety monitoring and early warning [9].

4.2. Collaborative upgrade of hardware and network

In terms of real-time monitoring and early warning for construction site safety, there is still considerable room for optimization in hardware and networks based on BIM and AI technologies. The synergistic effect between hardware and networks needs further improvement. Based on this, in its subsequent integrated development, researchers should also consider the collaborative upgrade of hardware and networks as a major development direction. To achieve this goal, researchers should first optimize the allocation of edge devices and cloud tasks based on actual conditions, enabling dynamic mobilization of computing resources [10]. At the same time, researchers should actively develop smaller, lower-power, and more adaptable smart sensor devices to reduce the deployment and maintenance costs of the integrated system. Additionally, in the process of real-time monitoring of construction site safety, researchers need to further upgrade the system's network technology to achieve higher data transmission speeds and lower latency, thus providing support for dynamic updates of BIM and AI models and further improving the real-time performance of monitoring and early warning tasks.

5. Conclusion

In summary, BIM and AI technologies are the most typical and advanced construction engineering management techniques in the field of modern informatization and intelligence. By introducing them reasonably into the construction site, combining actual conditions and safety management requirements, and effectively integrating them through the construction of an integrated system, an information-based and intelligent management plan can be developed for real-time monitoring of on-site construction safety, and a reasonable safety hazard warning and disposal process can be set up. This allows the advantages of BIM and AI technologies to complement each other, enabling scientific management of on-site construction safety. This approach ensures timely detection and handling of potential safety hazards in on-site construction, thereby maximizing construction safety.

Funding

"Research on AI-Intelligent Management Technology for Construction Safety Based on BIM Technology and Smart Construction Site Scenarios" (Project No.: KJQN202401904); "Research on Intelligent Monitoring System for Construction Quality and Safety Based on BIM and AI Technologies" (Project No.: 202412608006)

Disclosure statement

The authors declare no conflict of interest.

References

[1] Wang T, Yu T, Wang Y, et al., 2023, Planning of Smart Construction Site Monitoring System for Building Safety Construction. Popular Standardization, 2023(6): 170–172.

[2] Guo H, 2023, Exploration of GIS+BIM Management and Control Technology for Hazard Sources at Construction Sites. Journal of Guangdong Technical College of Water Resources and Electric Engineering, 21(4): 16–19,39.

[3] He K, 2024, Visualization Method of Remote Monitoring Data for Construction Sites Based on BIM Technology and Sensor Data Fusion. Construction Technology (Chinese and English), 53(19): 116–121.

[4] Wang A, 2025, Full-Process Monitoring Method for Construction Engineering Based on BIM Technology. Journal of Xuzhou Institute of Technology (Natural Science Edition), 40(1): 23–29.

[5] Li X, 2023, Application of BIM Technology in Safety Management of Deep Foundation Pit Construction Site.

Construction Science and Technology, 2023(22): 90–92.
[6] Liu J, 2025, Analysis of the Application of BIM Technology in Construction Site Management of Construction Engineering. Architecture and Construction, 4(3): 203–204.
[7] Luo S, Kong L, Xie Y, et al., 2024, Application Analysis of BIM Technology in Safety Management of Prefabricated Buildings. Anhui Architecture, 31(7): 98–99.
[8] Niu H, 2023, Exploration of Information-Based Supervision Method for Construction Quality Based on Big Data Technology. Jiangxi Building Materials, 2023(4): 372–373,376.
[9] Tang D, Li B, Wang S, 2024, Research on Construction Safety Evaluation Method Based on AI Intelligence Technology. Building Technique Development, 51(9): 141–143.
[10] Xue Q, 2025, Exploration of the Application of Smart Platforms in Construction Safety Management. City Development, 2025(4): 42–44.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Research on the Application of Local Materials in the Environmental Design of Rural Kindergartens

Liping Qin*, Baoxia Yu

Zhanjiang Preschool Education College, Zhanjiang 524084, Guangdong, China

**Author to whom correspondence should be addressed.*

Abstract: As the development of rural kindergarten education continues, creating an appropriate kindergarten environment has become an important issue. This paper focuses on the application of local materials in the design of rural kindergarten environments. Through in-depth research, it was found that local materials not only offer the advantages of being easily accessible and cost-effective but also enable the creation of learning and growth spaces for young children that are rich in regional characteristics. From indoor space layout, activity area division, to outdoor landscape design, the paper explores how to skillfully integrate local materials into design to stimulate children's curiosity and creativity, while enhancing their understanding and identification with local culture. This provides feasible strategies and methods for optimizing the environment of rural kindergartens, thereby contributing to the improvement of educational quality in rural kindergartens.

Keywords: Local materials; Rural kindergartens; Environmental design; Educational quality

Online publication: July 1, 2025

1. Introduction

In the rural education system, kindergartens serve as important venues for early childhood education, and their environmental design has a significant impact on children's growth and development [1]. Compared to urban kindergartens, rural kindergartens face certain limitations in resource acquisition. However, rural areas possess unique local material resources. These materials carry the historical and cultural heritage and natural characteristics of the region, presenting a unique opportunity for rural kindergarten environmental design. The reasonable use of local materials in kindergarten environmental design can effectively address the practical issues of limited construction funds and high material transportation costs in rural kindergartens. Additionally, it allows young children to be exposed to and experience the charm of local culture from an early age, fostering their love for their hometown and promoting their comprehensive development. Therefore, in-depth research on the application of local materials in rural kindergarten environmental design holds significant practical significance for promoting the distinctive characteristics and sustainable development of rural early childhood education [2].

2. The application of local materials in the interior design of rural kindergartens

2.1. The ingenious application of local wood

In the interior design of rural kindergartens, local wood is a highly valuable material. It possesses natural texture and grain, creating a warm and natural atmosphere for young children. For example, local wood can be used to craft furniture such as tables and chairs, whose unique texture allows children to experience the natural tactile sensation during use. Additionally, wood is easy to process and can be customized according to the kindergarten's spatial layout and activity requirements to create furniture that meets children's ergonomic needs, such as bookcases and storage cabinets suited to their height. Furthermore, wood has excellent acoustic properties, effectively absorbing noise to create a quiet learning and resting environment for children. From an aesthetic perspective, the color of local wood often blends with the rural environment, enhancing the continuity between indoor and outdoor spaces and giving the kindergarten's interior design a distinct regional character.

2.2. Flexible use of local bamboo materials

Bamboo, as a locally sourced material widely distributed in rural areas, has diverse applications in kindergarten interior design. It has a short growth cycle and is renewable, aligning with environmental sustainability principles. Bamboo blinds woven from bamboo can serve as interior partitions, effectively dividing spaces while maintaining visual connectivity, ensuring spatial transparency, and enabling children to interact across different activity zones. Bamboo can also be processed into bamboo strips to create uniquely shaped lighting fixtures, whose distinctive light and shadow effects can stimulate children's imagination. Additionally, bamboo toys and decorations are excellent choices, such as bamboo building blocks and small animal figurines. These are not only safe and non-toxic but also allow children to interact closely with local materials, understand their characteristics and origins, and cultivate an awareness and appreciation for local natural resources [3].

2.3. The distinctive presentation of local stone materials

Rural areas often have abundant local stone resources, and incorporating them into kindergarten interior design can create a unique effect. The hard texture of stone can serve as a contrasting element when combined with softer materials, enriching the material layers of the indoor space. For example, a small stone landscape can be set up at the entrance or in a corner, carved with simple patterns of plants and animals. This not only has aesthetic value but also serves as a tactile experience area for children, allowing them to feel the coolness and roughness of the stone. In terms of floor tiling, selecting appropriate local stone materials for mosaic designs can create playful patterns that guide children's movement while also serving a decorative purpose. Additionally, stone materials are durable, easy to clean, and highly suitable for high-traffic areas like kindergartens, effectively reducing maintenance costs.

2.4. The warmth of local textiles

Local textiles carry the cultural heritage and traditional craftsmanship of the region, adding warmth and familiarity to the kindergarten's indoor environment. Local cotton and linen fabrics can be used to make curtains, whose natural texture and soft colors complement the rural environment while regulating indoor lighting to create a comfortable visual environment for children. Additionally, cushions and seat pads made using local embroidery techniques, placed in reading corners or rest areas, are not only aesthetically pleasing and comfortable but also showcase local embroidery culture to children, exposing them to traditional culture from a young age. Furthermore, locally distinctive woven carpets, with their rich patterns and soft texture, can attract young children to play and engage in activities on them, adding vitality and fun to the indoor space and creating a child-friendly activity environment imbued with local cultural ambiance [4].

2.5. The vitality of local plants

Introducing local plants into the kindergarten indoor environment is a vivid simulation of the natural environment, allowing children to connect with nature. Based on indoor lighting and spatial conditions, suitable local potted plants such as succulents or *Pothos* can be selected and placed on windowsills, desktops, or suspended from the ceiling. These plants not only purify indoor air but also add a touch of vitality and greenery to the space. Set up a small plant corner in one corner of the classroom to showcase the growth process of native plants, such as the stages from seed germination to seedling growth. Allow children to participate in planting and caring for the plants to cultivate their observational skills and sense of responsibility. Additionally, the diverse shapes and colors of native plants can serve as teaching materials to guide children in recognizing the diversity of native plants, enhancing their understanding and love for the natural environment of their hometown. This transforms the kindergarten indoor environment into an important venue for children's natural education.

3. The application of local materials in the outdoor environment design of rural kindergartens

3.1. Creative application of local stone materials

In the outdoor environment design of rural kindergartens, local stone materials are highly practical and distinctive. Rural areas typically have a wide variety of local stone materials, such as bluestone, sandstone, and river pebbles. These stones possess a unique, rustic texture and natural patterns, which can create a simple, natural atmosphere in the kindergarten's outdoor space. Local stone can be used to pave pathways, with its irregular shapes and natural colors allowing children to feel the rhythm of nature while walking. Additionally, stone-paved surfaces have excellent drainage properties, preventing water accumulation during rain and ensuring children's safety. Furthermore, stone can be used to create small landscape sculptures or decorative elements, such as cute animal shapes or simple geometric patterns, to stimulate children's imagination and curiosity. Along the edges of activity areas, low stone benches can be constructed, combining aesthetic appeal with practicality, allowing children to sit and rest while observing the surrounding natural environment [5].

3.2. Diverse utilization of local wood

Local wood plays an irreplaceable role in the outdoor environment design of rural kindergartens, as it is readily available and has a natural, approachable quality. It can be used to construct large-scale playground equipment, such as climbing frames and swings. The natural texture of wood allows children to interact closely with natural materials while playing, feeling the warmth and texture of the wood. Additionally, wood has excellent elasticity and flexibility, providing children with a safe and reliable playground experience. Beyond playground equipment, wood can also be used to build resting pavilions, offering children and teachers a shaded and weather-protected space. In the design of the pavilions, local architectural styles can be incorporated, using traditional wooden structural techniques, allowing children to experience the charm of local culture from a young age. Furthermore, wood can be used to make flower boxes, planting colorful flowers and green plants, which can be placed in various outdoor corners. This not only beautifies the environment but also allows children to participate in plant care activities, fostering a sense of responsibility and compassion [6].

3.3. The ingenious use of local bricks

Local bricks are a common building material in rural areas. Incorporating them into the outdoor environment design of kindergartens can showcase a unique regional style. Old bricks or newly fired local bricks can be used to pave squares, activity areas, and other ground surfaces. Different laying patterns, such as herringbone or square designs, can create visually diverse effects, enhancing both the aesthetic appeal and the sense of playfulness in the flooring. Additionally, at the entrance or key landscape nodes of the kindergarten, brick walls with distinctive designs can be constructed. Simple patterns or text can be carved on the walls to introduce the kindergarten's cultural philosophy or local customs, serving an educational and guiding function. Furthermore, small planting beds can be constructed using bricks to grow local vegetables, fruits, and other crops, creating a labor practice area where children can experience the joy of planting, understand the growth process of local crops, and strengthen their connection to and love for their hometown's land.

3.4. Warm accents with local textiles

Local textiles, such as cotton-linen fabrics and handwoven items, can add warmth and vitality to the outdoor environment design of rural kindergartens. Hammocks made of cotton and linen can be hung in outdoor resting areas, allowing children to lie in them during leisure time, feel the gentle breeze, and enjoy a relaxing moment. Additionally, handwoven cushions and pillows can be used to decorate outdoor benches and steps, not only enhancing comfort but also showcasing local traditional craftsmanship. Furthermore, colorful local textiles can be used to create sunshades for outdoor activity areas, providing shade while their unique patterns and colors stimulate children's visual interest and create a cheerful, lively atmosphere. These textiles can also be changed according to seasons and activity themes, keeping the kindergarten's outdoor environment fresh and vibrant [7–9].

3.5. Ecological integration of local plants

Indigenous plants are an indispensable element in the outdoor environment design of rural kindergartens. They are adapted to the local climate and soil, and have the characteristics of being easy to grow and maintain. Representative indigenous trees, such as ginkgo and locust trees, can be selected as shade trees within the kindergarten. Their large canopies provide extensive shaded areas for children, while also serving as habitats for numerous bird species, allowing children to observe natural ecosystems up close. When selecting shrubs, flowering shrubs like roses and crabapples, which feature vibrant colors and extended blooming periods, can be planted in flower beds and borders within the kindergarten grounds, adding color and fragrance to the environment. Additionally, native herbaceous plants, such as lavender and cosmos, can be planted in large areas on open grounds or slopes to create a flower field landscape, attracting butterflies, bees, and other insects, thereby constructing a vibrant ecological system. These plants can also serve as vivid educational materials for nature education. Teachers can guide children in recognizing plant names and characteristics, observing plant growth changes, and cultivating their scientific exploration spirit and environmental awareness [10].

4. Conclusion

After conducting an in-depth study on the application of local materials in the environmental design of rural kindergartens, a profound understanding of the potential and value inherent in this design approach was gained. It not only vividly showcases regional cultural characteristics, endowing rural kindergartens with a unique charm, but also inspires children's curiosity and desire to explore the world around them through the natural qualities of these materials. From a practical perspective, the use of local materials significantly reduces construction and maintenance costs, aligning perfectly with the economic realities of rural areas and laying a solid foundation for the sustainable development of rural early childhood education. In the educational dimension, as children engage closely with local materials, they gradually develop a sense of love for their hometown and cultural identity, which undoubtedly provides them with spiritual nourishment for their future growth. Looking ahead, further collaboration between designers and educators is anticipated to deeply explore the potential of local materials, continuously innovate, and design more high-quality environments suitable for rural kindergartens. This will create a more vibrant and colorful growth environment for rural children, helping them thrive under the nurturing influence of local culture while also injecting sustained vitality into the development of rural education.

Funding

"Guangdong Province 2022 Rural Kindergarten Quality Improvement Project" Rural Kindergarten Environment Creation Practice Research (Project No.: 2022XCYEYA01)

References

[1] Li C, 2025, Research on the Application of Color in the Design of Modern Urban Kindergarten Environments, thesis, Northeast Normal University.

[2] Zhang Y, 2025, A Study on the Characteristics and Functional Applications of Folk Toys in Kindergarten Design, thesis, Zhongyuan University of Technology.

[3] Wan L, 2013, The Application of Bamboo Culture in Early Childhood Education. Fei: Quality Education, 2013(10): 1.

[4] Wu T, Kang J, 2022, The Application of Paper Art in Kindergarten Spatial Environment Design. China Pulp and Paper, 2022(2).

[5] Yao L, Qiao X, 2020, Analysis of the Application of Eco-friendly Materials in Kindergarten Spatial Environment Design: A Case Study of the Four-leaf Clover Home Kindergarten. Sichuan Building Materials, 46(4): 3.

[6] Lu S, Yue S, 2022, Research on the Application of Indoor Decorative Materials in Kindergartens Based on Child-Friendly Concepts. Art and Technology, 2022(006): 035.

[7] Wang Z, 2018, Research on Localization in Kindergarten Environmental Design Education. Charm of China, 2018(001): 107.

[8] Chen Y, 2025, Research on Green Design of Indoor Spatial Environments in Kindergartens, thesis, Xi'an University of Architecture and Technology.

[9] Fu Y, 2019, Research on Indoor and Outdoor Environment Design in Kindergartens Based on Child Psychology, thesis, Shenyang University of Architecture.

[10] Lin F, 2016, Research on the Application of Paper Art in the Creation of Kindergarten Environments, thesis, Shaanxi Normal University.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Research on Multi-functional Excavation Trolley for Single-track Tunnel Face

Guangming Zhang*

HanJiang Heavy Industry Co., Ltd of CR11G, Xiangyang 441006, Hubei, China

**Author to whom correspondence should be addressed.*

Abstract: The construction of the tunnel face is a critical aspect of tunnel excavation, and its supporting equipment mainly includes drilling jumbos, arch installation trolleys, wet spraying manipulators, and anchor bolt trolleys. To address the issues of high construction costs and the need to replace equipment for different processes, this paper designs an economical and practical multi-functional integrated trolley based on engineering cases. This trolley is suitable for various construction methods such as full-face excavation and benching method, and integrates functions such as drilling and blasting holes, anchor bolt holes, advance grouting holes, pipe roof construction, charging, anchor bolt installation and grouting, and arch mesh installation. It reduces the number of operators, improves the tunnel working environment, lowers construction costs, and enhances construction efficiency.

Keywords: Single-track tunnel; Tunnel face; Excavation trolley; Full-face excavation; Benching method

Online publication: July 1, 2025

1. Introduction

Tunnel construction is gradually moving towards mechanization, automation, and intelligence to improve construction quality, safety, and efficiency [1–3]. For complex strata, to achieve requirements such as "quality, safety, progress, and environmental protection", it is necessary to comprehensively consider factors such as tunnel length, section size, surrounding rock geology, excavation method, schedule requirements, environmental and site conditions, and to configure construction machinery in an economically applicable and overall efficient manner. Currently, the equipment used for tunnel face construction has issues such as poor adaptability, single functionality, low overall efficiency, and high cost:

(1) Most equipment can only meet the needs of full-face and two-bench excavation methods, resulting in poor adaptability [4].

(2) Apart from the three-arm drilling jumbo, which can handle both excavation and anchor bolt construction, other equipment generally only has one function [5, 6].

(3) Different equipment needs to be replaced for different work procedures, leading to more ineffective working time and affecting overall efficiency [7, 8].

(4) The equipment is costly, resulting in high construction costs. To address these issues, it is necessary to further improve the construction technology of the tunnel face, optimize and upgrade existing equipment, or develop new multi-functional equipment to enhance the overall efficiency of tunnel face construction and reduce construction costs.

In response to the aforementioned issues, a multi-functional tunnel construction equipment that integrates various functions such as tunnel drilling and arch installation is developed. This equipment not only facilitates workers to load explosives but also allows other process equipment to pass through the gantry, significantly improving the efficiency of tunnel excavation using the drilling and blasting method. Compared with traditional equipment, this multi-functional equipment can effectively reduce equipment procurement and maintenance costs for tunnel construction, facilitate equipment scheduling in narrow tunnels, and save time and labor. The adoption of integrated equipment will significantly increase excavation speed, ensure construction safety, reduce operational complexity caused by excessive equipment, optimize construction processes, improve construction accuracy, and ensure the quality of tunnel sections.

2. Scheme design and key technology research

2.1. Scheme design

The single-track multi-functional excavation trolley mainly consists of a traveling mechanism, a platform frame, a movable arch frame, an arch frame lifting mechanism, an arch frame hoisting mechanism, an arch frame transfer cart, an arch frame installation cart, an anchor bolt auxiliary drilling mechanism, auxiliary mechanisms, an electrical system, and a hydraulic system. **Figure 1** shows the movable arch frame in retracted state, while **Figure 2** shows the movable arch frame in an extended state. This equipment is suitable for both full-face and benching method construction, integrating tasks such as assisting manual pneumatic drilling and blasting holes, anchor bolt holes, charging, anchor bolt installation and grouting, and arch mesh installation.

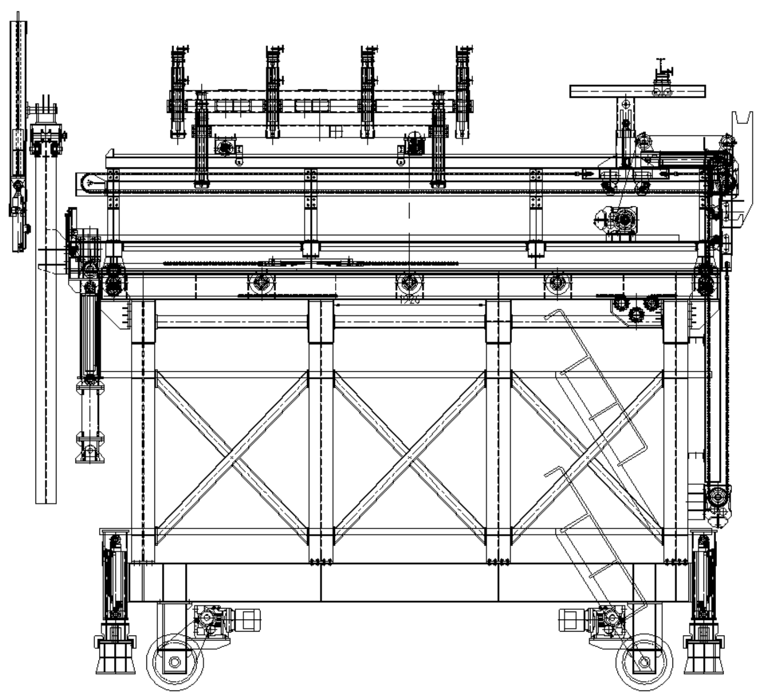


Figure 1. Mobile arch frame in retracted state

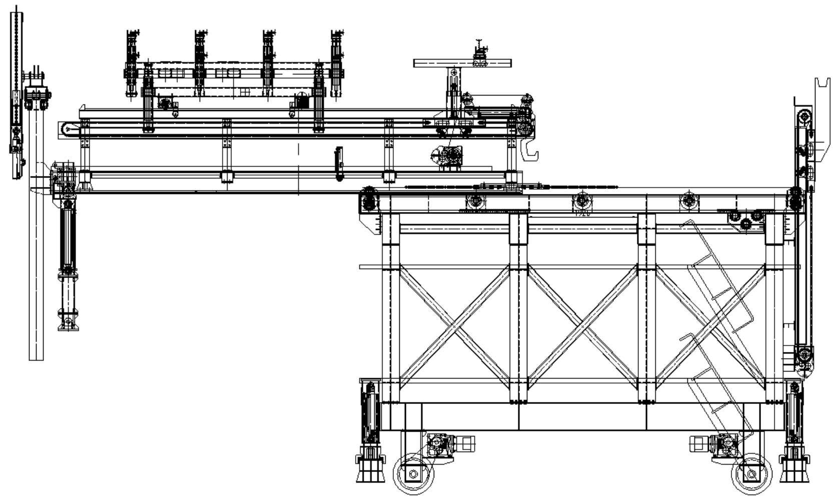


Figure 2. Mobile arch frame in extended state

2.2. Key technical research

(1) Research on telescoping arch frame

The mobile arch frame consists of a frame structure composed of 4 sets of arch frames and longitudinal beams (**Figure 3**). The lower end of the arch frame is equipped with a load-bearing track connected to the gantry beam. The load-bearing track is equipped with tug wheels and reverse hanging wheels, which are driven by chains to achieve relative movement between the arch frame and the gantry. The front end of the arch frame is equipped with telescoping legs. During stepped construction, the arch frame extends to support the upper step.

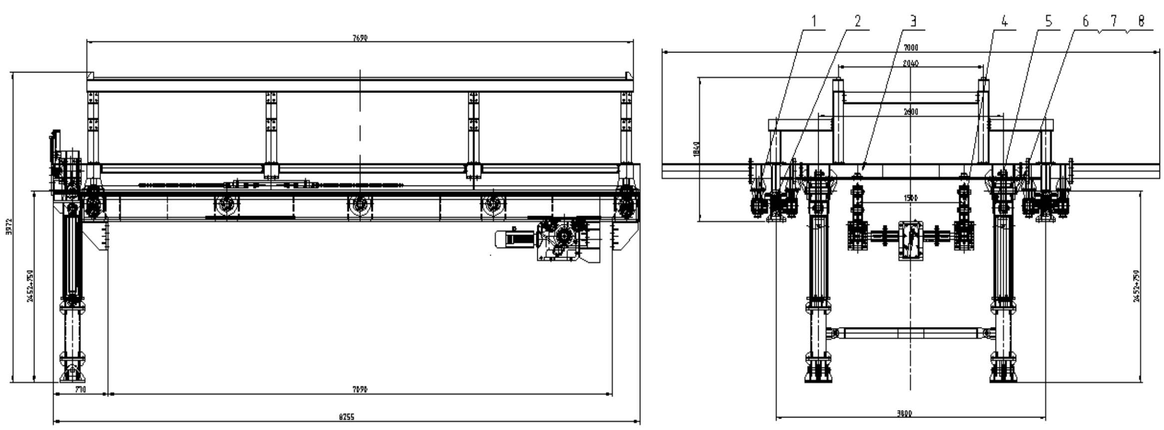


Figure 3. Schematic diagram of telescoping arch frame

(2) Research on arch frame transfer

The arch frame transfer mechanism includes a lifting mechanism (**Figure 4**), a transfer cart, and an installation cart. The arch frame lifting mechanism consists of a guide frame, a lifting cart, and a driving mechanism, with a total of two sets installed on the rear columns of the trolley platform, mainly used to lift the arch frame from a low position to a high position, facilitating the transfer of the arch frame on the platform by the arch frame transfer cart. The effective lifting height of the mechanism is 2.5m.

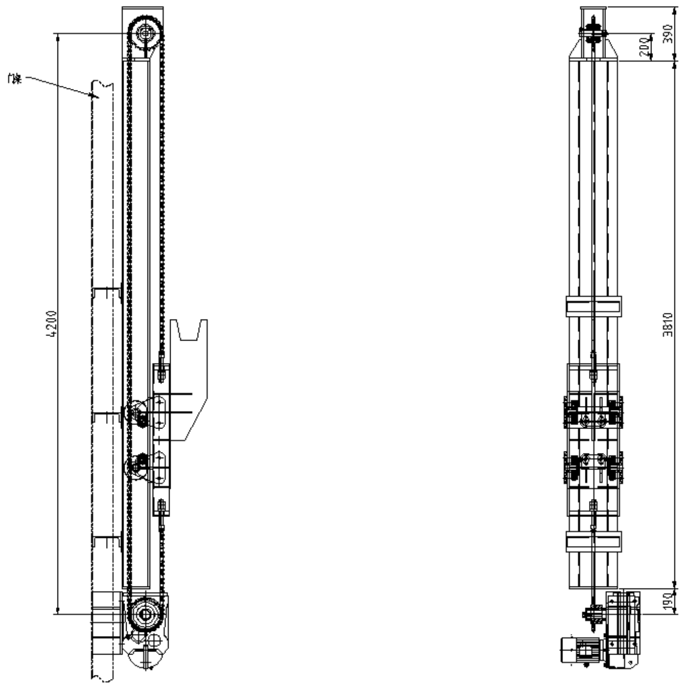


Figure 4. Schematic diagram of arch frame lifting mechanism

The arch frame transfer cart (**Figure 5**) mainly consists of a running track, a driving mechanism, and a cart, with a total of two sets installed on both sides of the mobile arch frame. It is mainly used to transfer the arch frame from the lifting mechanism to the arch frame installation cart.

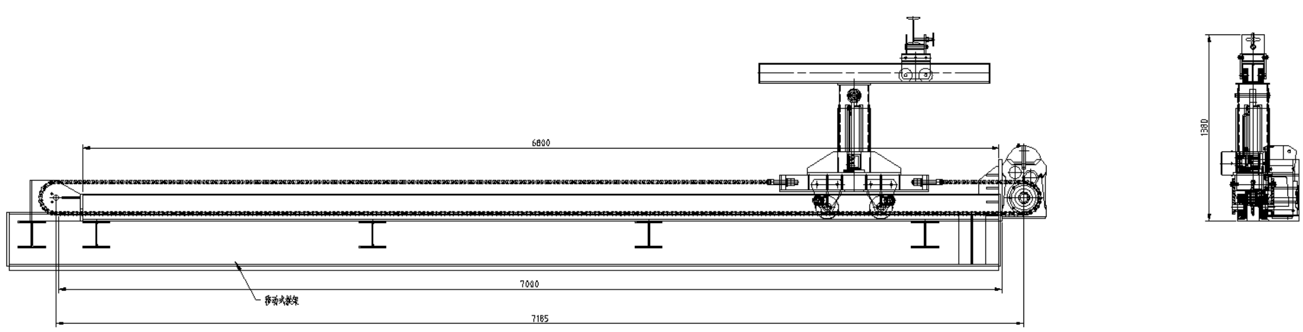


Figure 5. Schematic diagram of arch frame transfer cart

The arch frame installation cart (**Figure 6**) mainly consists of a running mechanism, a cart frame, an arch frame lifting mechanism, and an arch frame swing mechanism. It is mainly used for the storage and installation of arch frames, realizing the adjustment of different spacings, lifting, and small-scale swinging of the arch frames.

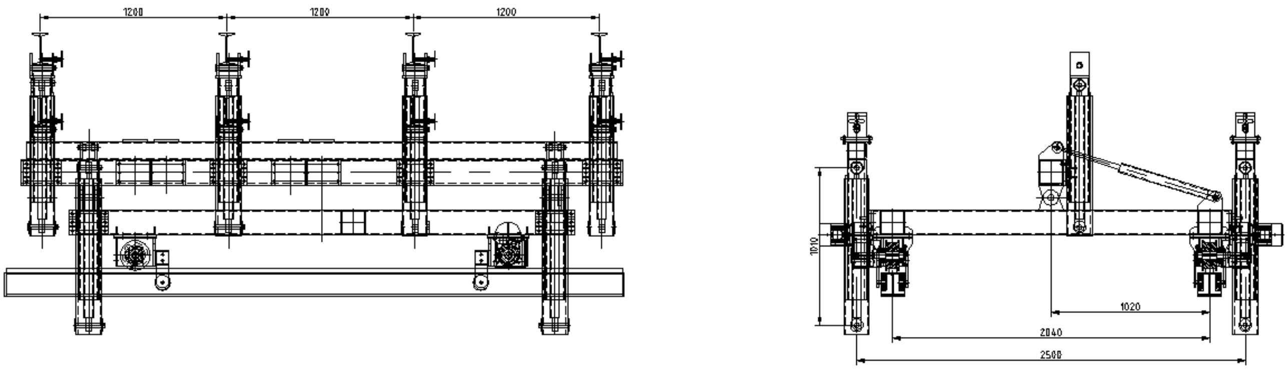


Figure 6. Schematic diagram of arch frame installation cart

2.3. Calculation of mechanical parameters

Steel is Q235B steel with a gravity density of 78.5kN/m3, an elastic modulus of 206Gpa, an allowable tensile and compressive stress of 140Mpa, and an allowable bending stress of 156Mpa (with a safety factor of 1.5). Some moving mechanism parts are made of 45# steel with an allowable tensile and compressive stress of 210Mpa. The construction load consists of the structural self-weight load and the weight of the steel arch frame, with a single steel arch frame weighing 500kg.

Focusing on the large cantilever state of the telescoping arch frame, the stiffness and strength of the platform and telescoping arch frame structure are checked. At this time, the equipment has completed the lifting of 4 steel arch frames, and the front legs have not yet supported the ground to form a stable structure. The equipment is in the most unfavorable stress state overall. **Figure 7** shows the finite element model of the trolley in working condition.

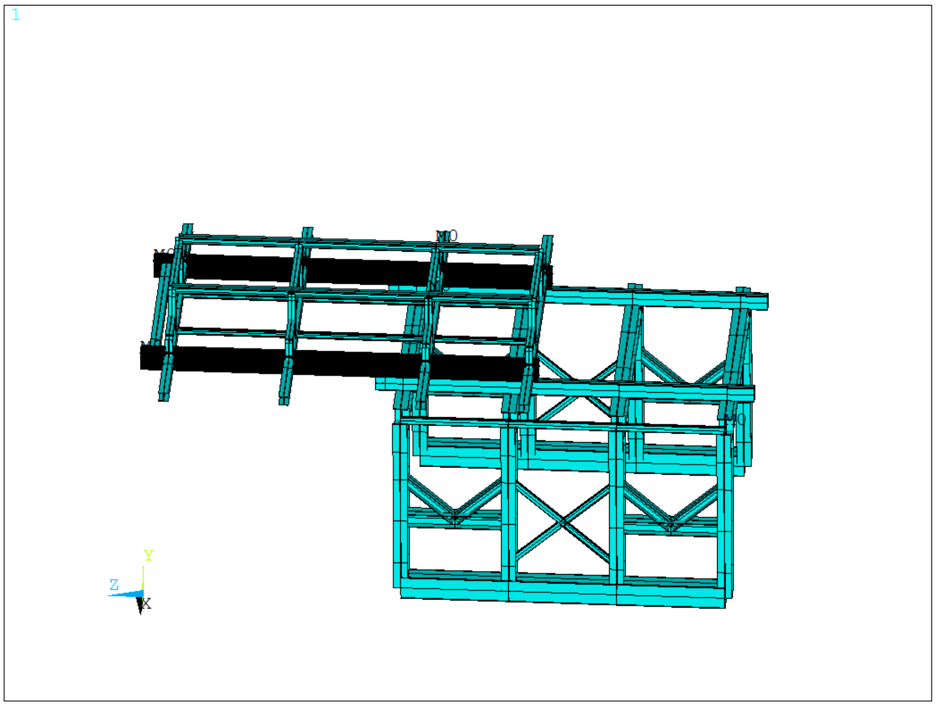
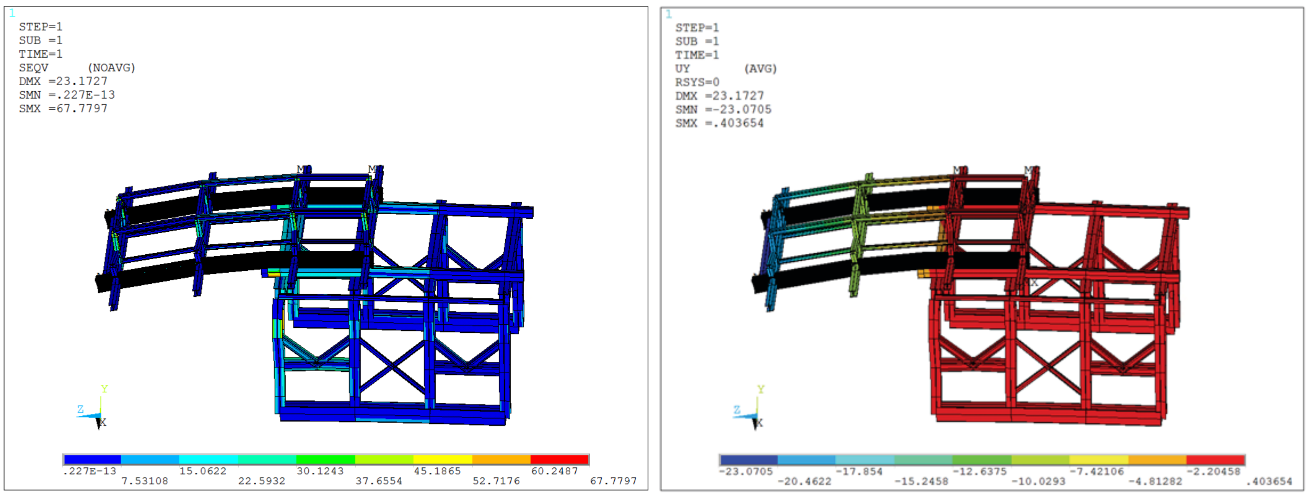


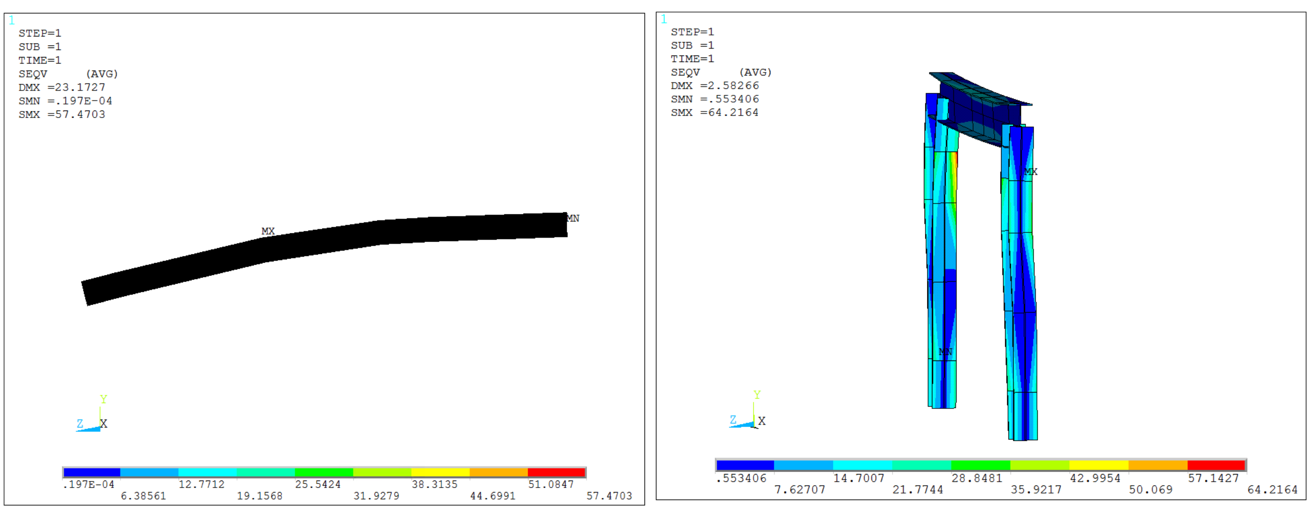
Figure 7. Finite element model

When the equipment is in a horizontal state, the finite element calculation results are shown in **Figure 8(a)** and **Figure 8(b)**, and the stress calculation results for key structures are shown in **Figure 9(a)** and **Figure 9(b)**. The maximum stress is 68Mpa, and the maximum deformation is 23mm, which meets the usage requirements.



(a) (b)

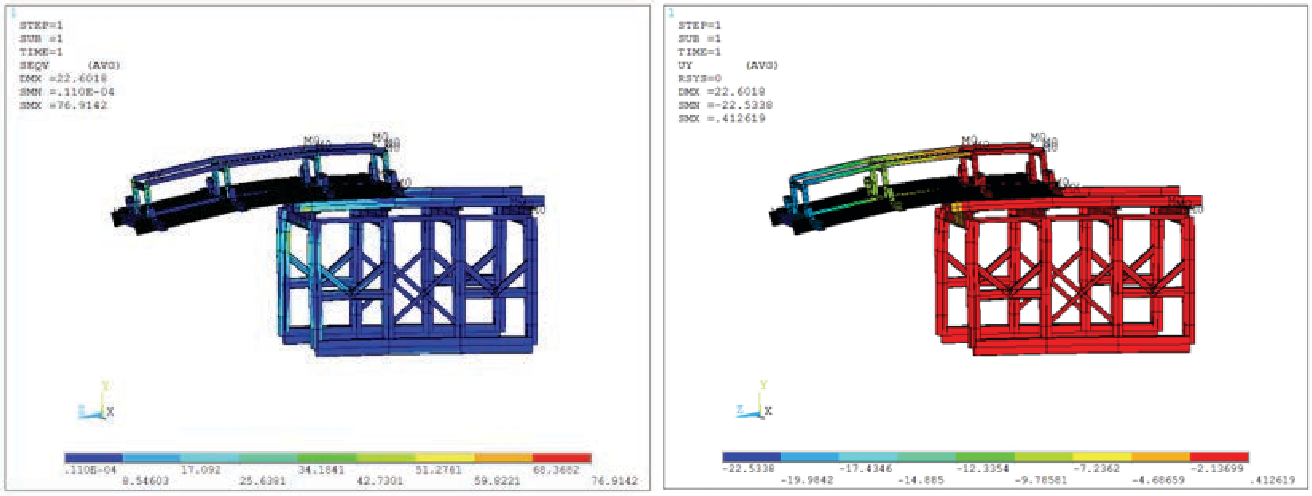
Figure 8. Finite element calculation results when equipment is in horizontal state, (a) Stress calculation results for the complete machine; (b) Deformation calculation results for the complete machine



(a) (b)

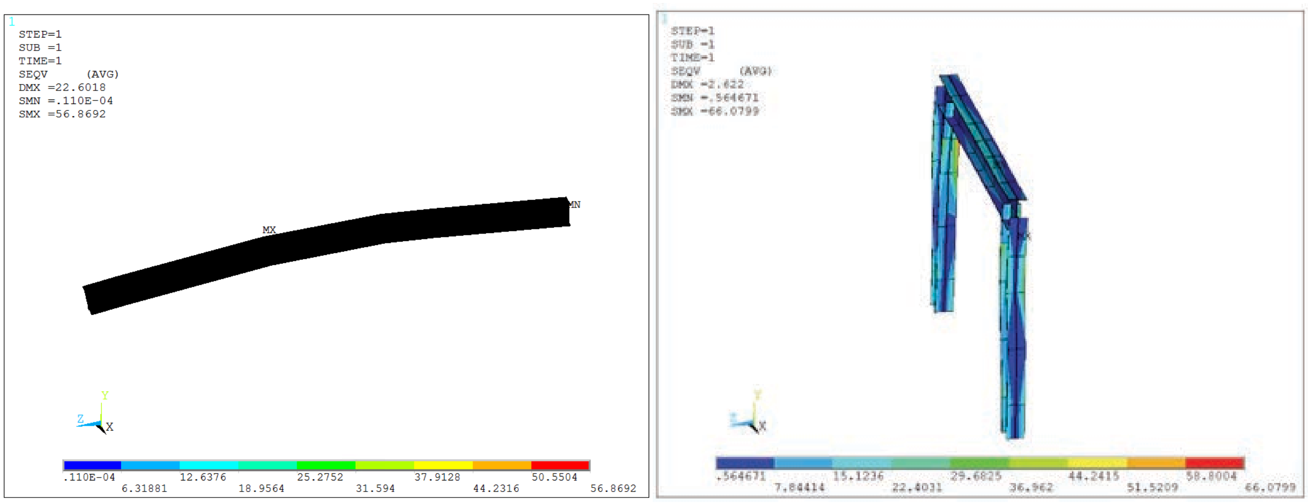
Figure 9. Stress calculation results for key structures when equipment is in horizontal state, (a) Calculated stress for the front longitudinal beam; (b) Calculated stress for the first gantry frame

The road conditions of the tunnel face are complex, with large slopes, and a maximum slope of 11%. The stress conditions of the equipment when climbing an 11% slope are calculated. The finite element calculation results are shown in **Figure 10(a)** and **Figure 10(b)**, and the stress calculation results for key structures are shown in **Figure 11(a)** and **Figure 11(b)**. The maximum stress is 76Mpa, and the maximum deformation is 22.6mm, which meets the usage requirements.



(a) (b)

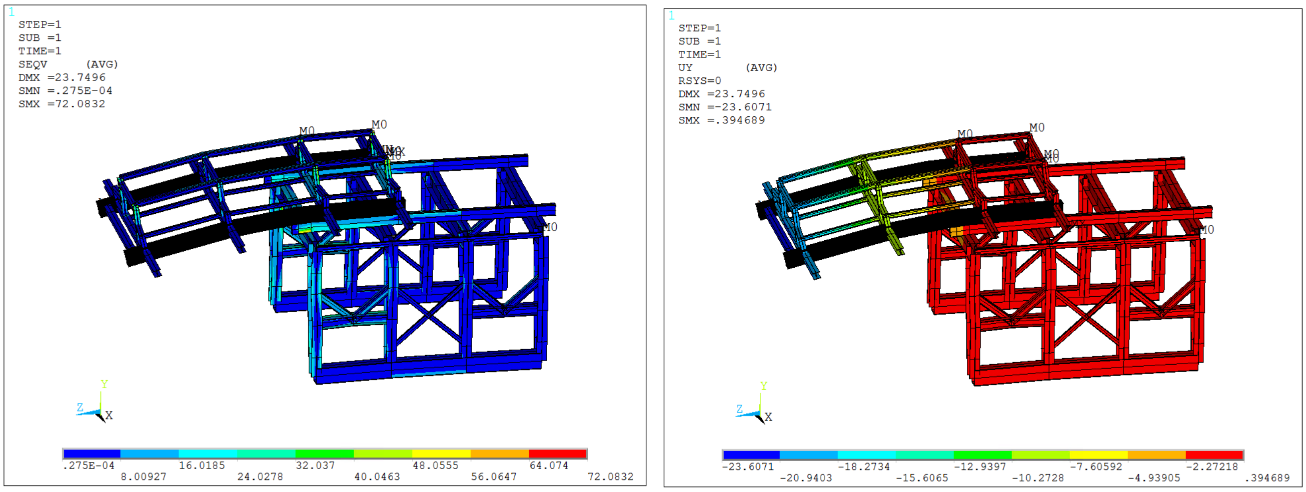
Figure 10. Finite element calculation results of equipment when climbing at an 11% slope, (a) Stress calculation results for the complete machine; (b) Deformation calculation results for the complete machine



(a) (b)

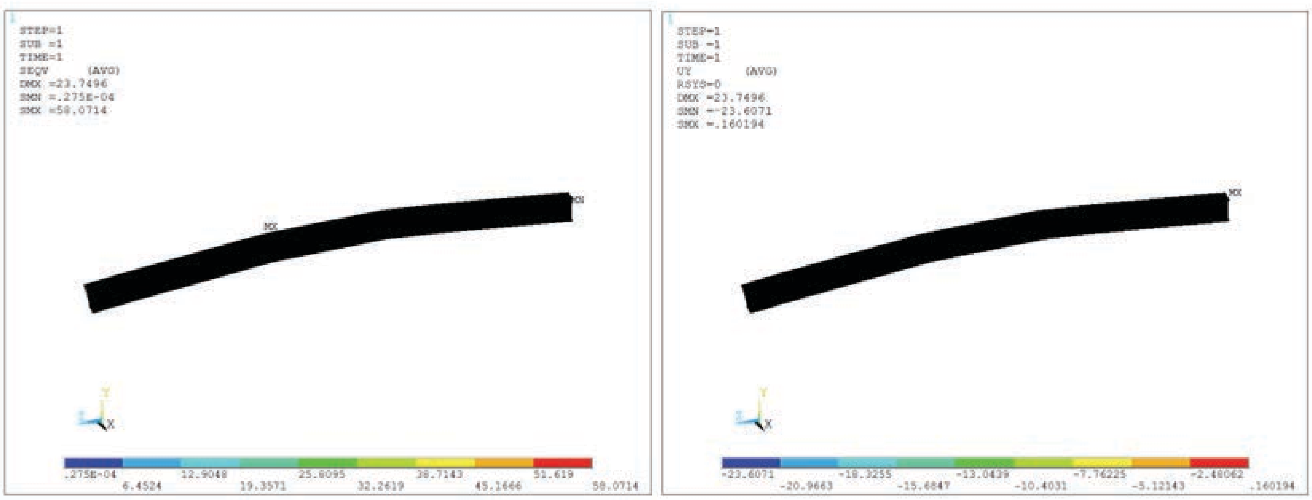
Figure 11. Stress calculation results for key structures of equipment when climbing at an 11% slope, (a) Calculated stress for the front longitudinal beam; (b) Calculated stress for the first gantry frame

The stress conditions of the equipment when descending an 11% slope are calculated. The finite element calculation results are shown in **Figure 12(a)** and **Figure 12(b)**, and the stress calculation results for key structures are shown in **Figure 13(a)** and **Figure 13(b)**. The maximum stress is 72Mpa, and the maximum deformation is 23.6mm, which meets the usage requirements.



(a) (b)

Figure 12. Finite element calculation results of equipment when descending at an 11% slope, (a) Stress calculation results for the complete machine; (b) Deformation calculation results for the complete machine



(a) (b)

Figure 13. Stress calculation results for key structures of equipment when descending at an 11% slope, (a) Calculated stress for the front longitudinal beam; (b) Calculated stress for the first gantry frame

The force models used in the above mechanical analysis process are calculated using simplified methods that tend to be safe. After analysis, all components can meet the stress and deformation requirements.

3. Research on construction technology

3.1. Research on drilling technology for tunnel face

(1) Full-face construction

As shown in **Figure 14**, the mobile arch frame is retracted, and manual drilling operations on the tunnel face are performed using pneumatic rock drills through the working platform of the trolley.

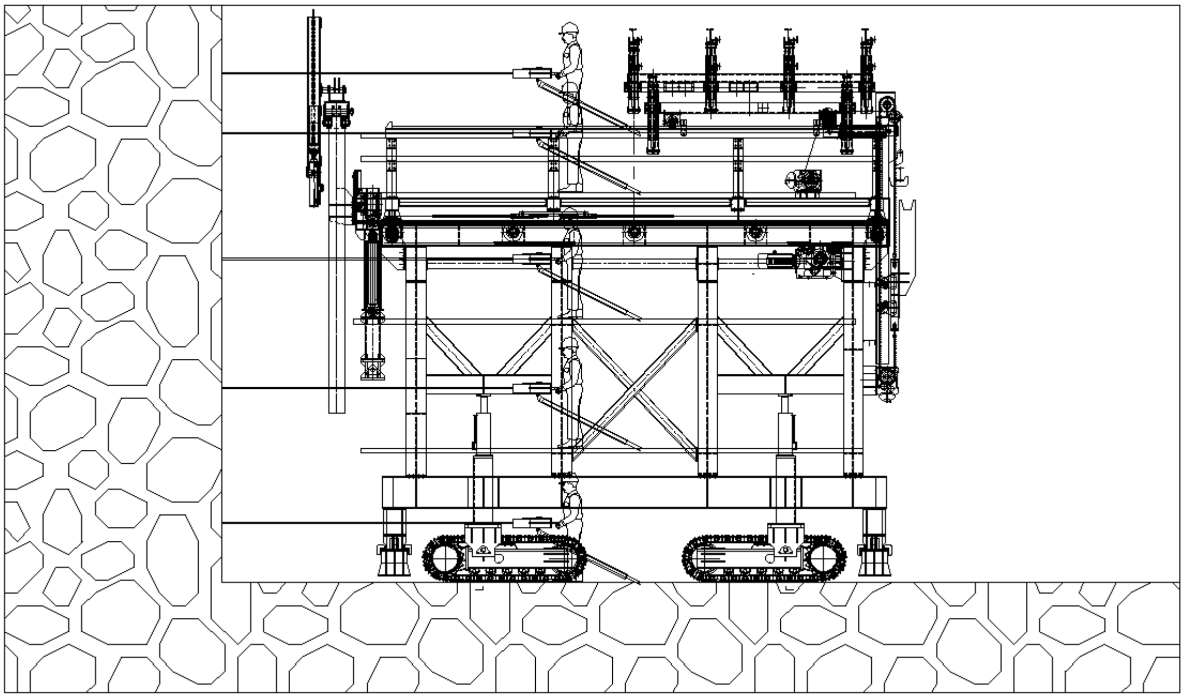


Figure 14. Full-face drilling

(2) Stepped construction

As shown in **Figure 15**, the mobile arch frame is extended, and the front legs of the arch frame are supported on the upper step. Manual drilling operations on the tunnel face are performed using pneumatic rock drills through the working platform of the trolley.

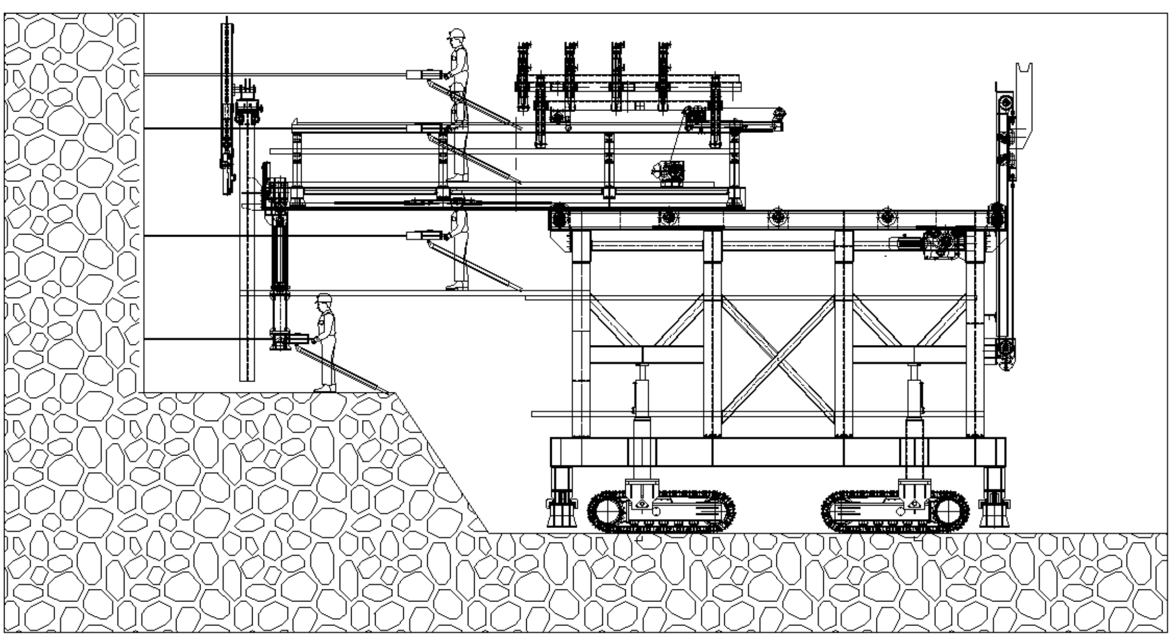


Figure 15. Stepped drilling

3.2. Research on arch frame assembly process

3.2.1. Full-face construction

(1) S1: The multi-functional integrated excavation trolley is positioned away from the tunnel face, and the arch frame is pre-assembled on the ground (excluding the lower part of the arch wall) without affecting the traffic of construction vehicles at the tunnel face.

(2) S2: The pre-assembled arch frame is lifted from the ground to a vertical position using the arch frame lifting mechanism at the rear of the trolley.

(3) S3: After the arch frame is lifted to a certain height by the lifting mechanism, it is placed on the arch frame lifting mechanism with manual assistance and lifted to the highest position.

(4) S4: Once the arch frame is lifted to the highest position, it is moved from the lifting mechanism to a transport cart.

(5) S5: The transport cart continues to lift the arch frame to a higher position and transports it to the installation cart for temporary storage.

(6) S6: Pre-assemble four arch frames following the same steps as above.

(7) S7: When the tunnel face meets the conditions for arch frame installation, the trolley is moved to the vicinity of the tunnel face. The arch frame is then moved to the installation position using the installation cart, and adjustments such as lifting and swinging are made. The side arch frames are pushed to the side walls of the tunnel using a telescoping platform, and the bottom arch frames are installed with manual assistance.

3.2.2. Benching method construction

(1) S1: The multi-functional integrated excavation trolley operates away from the tunnel face, and the arch frame is pre-assembled on the ground without affecting the traffic of construction vehicles at the tunnel face.

(2) S2: The assembled arch frame is lifted from the ground to a vertical position by the arch frame lifting mechanism at the rear of the trolley.

(3) S3: After the arch frame is lifted to a certain height by the lifting mechanism, it is manually placed on the arch frame lifting mechanism, which then lifts the arch frame to the highest position.

(4) S4: Once the arch frame is lifted to the highest position, it is moved from the lifting mechanism to a transport cart.

(5) S5: The transport cart continues to lift the arch frame to a higher position and then transports it to the arch frame installation cart for temporary storage.

(6) S6: Complete the pre-assembly of four arch frames according to the same steps as above.

(7) S7: When the tunnel face meets the conditions for arch frame installation, the trolley is moved to the vicinity of the tunnel face. The arch frame is extended onto the bench, and after the support legs are properly positioned, the arch frame is moved to the installation position using the installation cart. Adjustments such as lifting and swinging are then made. The bottom arch frames on the bench are installed with manual assistance.

3.3. Research on anchor drilling technology

After the completion of the arch frame, the anchor drilling operation is performed using the anchor assist mechanism at the front of the trolley. The anchor drilling mechanism can move back and forth through the telescoping arch frame to complete anchor drilling operations at different locations.

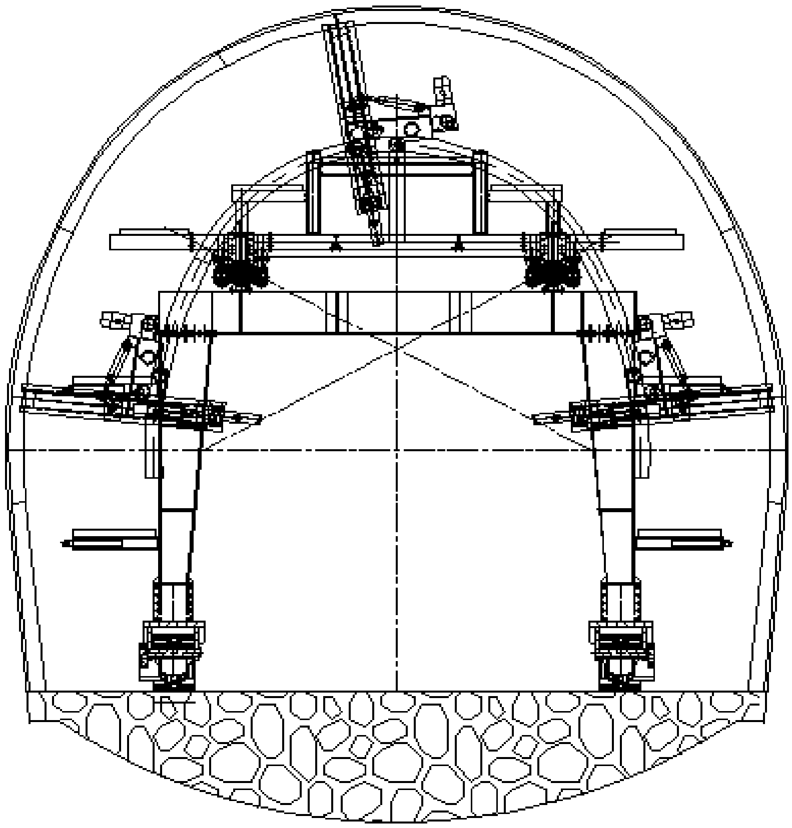


Figure 16. Schematic diagram of anchor drilling

4. Engineering example

4.1. Application situation

The main line of the Sichuan-Tibet Section 7 project is 36.645km long, with a tunnel length of 35.4km, accounting for 96.6% of the total line length. Among them, the Ga'er Temple Tunnel is a key and difficult project of the entire line, with a total length of 18.8km and a maximum depth of 1093m. The main geological problems include fault fracture zones, large deformations in soft rock with high ground stress, high ground temperature, sudden water inrush, and bedding bias pressure. Among them, large deformations in soft rock are the most prominent issue, and the predicted ground stress is the highest along the entire line, reaching 54.8MPa.

The prototype designed and produced based on the scheme of the single-track multi-functional integrated excavation trolley is mainly used for the tunnel face construction of the small-mileage left tunnel of the No.5 inclined shaft of the Ga'er Temple Tunnel in the Sichuan-Tibet Section 7. The equipment arrived at the site in May 2023 and was ready for use at the end of May. **Figure 17** shows the operating status of field equipment.

Figure 17. Operating status of field equipment

4.2. Cost analysis

The initial investment for purchasing a rock drilling jumbo is significant. A three-arm rock drilling jumbo (without a computer) costs over 9 million yuan, while a semi-computerized or fully computerized three-arm rock drilling jumbo can cost over 10 million yuan. (The fully computerized rock drilling jumbo from Railway Construction Heavy Industry costs 11.6 million yuan.)

Table 1 lists the cost of the newly developed multi-functional tunnel excavation platform. It compares the costs of various tunnel machinery currently used in different stages of drilling and blasting construction. Through comparison, it is evident that the multi-functional tunnel excavation platform has a significant cost advantage.

Table 1. Equipment cost comparison table

<table>
<tr><th colspan="2">Equipment</th><th>Three-boom jumbo</th><th colspan="2">Steel arch carrier</th><th>Wet spraying manipulator</th><th>Bolting jumbo</th><th>Total</th></tr>
<tr><td colspan="2"></td><td>1160 × 2</td><td colspan="2">250</td><td>160</td><td>260</td><td>2990</td></tr>
<tr><th rowspan="2">Equipment</th><th colspan="7">Comprehensive excavation platform (Estimated cost)</th></tr>
<tr><th>Framework structure</th><th>Working arm + Drilling hammer</th><th>Hydraulic system</th><th>Control system</th><th>3D laser radar scanning</th><th>Arch installation system</th><th>Total</th></tr>
<tr><td></td><td>100</td><td>50 × 6</td><td>40</td><td>80</td><td>80</td><td>50</td><td>650</td></tr>
</table>

5. Conclusion

In conclusion, the development of a multi-functional excavation trolley for single-track tunnel face construction addresses critical limitations in existing tunnel equipment, including high costs, limited functionality, and operational inefficiencies. By integrating multiple construction processes, such as drilling, grouting, anchor installation, and arch frame assembly, into a single platform, this innovative design enhances construction flexibility, reduces labor intensity, and improves safety and overall efficiency. Mechanical analysis confirms the trolley's structural reliability under various working conditions, and practical application in the Ga'er Temple Tunnel project demonstrates its cost-effectiveness and adaptability in complex geological environments. This research provides a valuable reference for future mechanized and intelligent tunnel construction practices.

Disclosure statement

The author declares no conflict of interest.

References

[1] Huang Y, 2020, Structural Design and Simulation Optimization of the Working Mechanism of an Arch Installation Trolley, thesis, Xihua University, 2020(01).

[2] Luo K, 2013, Kinematics and Dynamics Research on Arch Installation Manipulator, thesis, Southwest Jiaotong University, 2013(11).

[3] Li Y, 2011, Design and Research on Steel Arch Installation Trolley, thesis, Henan University of Science and Technology, 2011(09).

[4] Zhang G, Li D, Lei X, 2022, Research on Key Technologies of Foldable Steel Arch and Arch Erection Suitable for Tunnel Mechanized Construction. Tunnel Construction / Suidao Jianshe (Zhong-Yingwen Ban), 42(3): 445. DOI: 10.3973/j.issn.2096-4498.2022.03.013.

[5] Ni P, 2020, Research and Application of New Tunnel Support Equipment – Steel Arch Installation Trolley. China Equipment Engineering, 2020(18): 2. DOI: CNKI:SUN:SBGL.0.2020-18-007.

[6] Jiang C, Shi X, Lu X, et al., 2020, Research Status and Development Trend of Arch Trolley. Construction Machinery (First Half of the Month), 2020(009): 12–15.

[7] Li Y, Ren D, Xu L, 2011, Design and Simulation Analysis of Steel Arch Installation Mechanism Based on Virtual Prototype. Lifting and Transportation Machinery, 2011(1): 32–36.

[8] Di M, 2006, Rapid Construction and Machinery Matching Technology at the Entrance of Dingshuiba Tunnel. Science and Technology Information Development and Economy, 16(8): 295–296.

Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Research on the Optimization and Simulation of Assembly Line Balancing Based on Improved PSO Algorithm

Wenkang Zhang*

School of Management, Shandong University of Technology, Zibo 255049, Shandong, China

**Author to whom correspondence should be addressed.*

Abstract: In response to the deficiencies of commonly used optimization methods for assembly lines, a production demand-oriented optimization method for assembly lines is proposed. Taking a certain compressor assembly line as an example, the production rhythm and the number of workstations are calculated based on production requirements and working systems. With assembly rhythm and smoothing index as optimization goals, an improved particle swarm optimization algorithm is employed for process allocation. Subsequently, Flexsim simulation is used to analyze the assembly line. The final results show that after optimization using the improved particle swarm algorithm, the assembly line balance rate increased from 71.1% to 85.9%, and the assembly line smoothing index decreased from 47.4 to 29.8, significantly enhancing assembly efficiency. This demonstrates the effectiveness of the proposed optimization method for the assembly line and provides a reference for other products in the same industry.

Keywords: Assembly line balance; Improve PSO; Simulation optimization

Online publication: July 1, 2025

1. Introduction

As the main body of the real economy, the high-quality development of the manufacturing industry is the key to promoting the high-quality development of the whole economy. Although China's manufacturing industry is large in scale, it is not yet fully sound. It faces problems such as uneven products, high resource consumption, and overcapacity, which pose a more severe challenge to China's manufacturing industry [1]. In view of this situation, the production practice in Japan, Europe and the United States and other countries has proved that the use of lean production can effectively improve the adaptability and management level of enterprises to the market, reduce waste and enhance production flexibility, promote enterprises to establish an effective operation mechanism for continuous improvement in daily production and operation, flexibly and efficiently face market changes, and ensure the competitive advantage of enterprises [2].

As a new intelligent heuristic algorithm, particle swarm optimization is favored by many scholars at home and abroad. Yu *et al.* aimed at the low efficiency of the production line, through the establishment of the actual model of on-site production, the particle swarm optimization algorithm was used to solve the problem, and finally the production line gave full play to the maximum efficiency [3]. Xiao *et al.* proposed an improved particle swarm optimization algorithm for the second type of assembly line balancing problem, established a mathematical model with the optimization goal of minimizing the beat and the standard deviation of station load, and finally effectively verified the rationality of the scheme [4]. In order to improve the driving stability of four-wheel drive vehicles, Yang *et al.* proposed a fuzzy proportional integral differential control system based on an improved particle swarm optimization algorithm, and simulated and verified the output effect of the optimized control system [5]. Luo *et al.* used particle swarm optimization to solve the problems of production bottleneck and low balance rate of production line, so as to double the production capacity [6]. Ankitad *et al.* proposed a BA PSO to solve the scheduling problem of computational grid and improve the utilization of resources [7]. Wang *et al.* proposed a multi-objective motion optimization strategy based on improved particle swarm optimization algorithm, and proved the effectiveness of the method through experiments [8].

Zhao *et al.* optimized the total loss of LCLC resonant converter based on the particle swarm optimization algorithm, and built LCLC resonant converter with optimized parameters [9]. Shojaie *et al.* proposed the combination of particle swarm optimization algorithm and parallel simulated annealing algorithm to solve the dual objective equipment layout problem more effectively [10]. Aydoğan *et al.* proposed a new particle swarm optimization algorithm to solve the U-line balance problem with random task time. The performance of the proposed method is compared with the existing methods in the literature [11]. Yang *et al.* designed an improved multi-objective particle swarm optimization algorithm to solve the problem of uncertainty widely existing in the process of ship plane section construction, and verified the effectiveness of the method through the actual test [12]. Liu *et al.* proposed a multi-objective particle swarm optimization algorithm based on target space partition to solve the facility layout problem with unequal area [13]. Yang *et al.* effectively solved the problem of disorderly and inefficient multi-objective sequencing of mixed model production lines by introducing the improved particle swarm optimization algorithm [14].

To sum up, scholars at home and abroad have carried out a lot of research and practice using the application of PSO, but by combing the literature, it is found that most of the literature only uses PSO algorithm to optimize the assembly line or other fields, and the research on the combination of intelligent optimization algorithm and Simulation Technology is less. In view of this, this paper selects the compressor assembly line of a manufacturing enterprise as the research object. By analyzing the current problems of the assembly line, an improved PSO is designed to optimize the balance of the assembly line. The effectiveness is then verified through simulation software to enhance assembly efficiency.

2. Current status of the assembly line

2.1. Select survey subjects

The subject of this study is a high-tech enterprise that integrates research and development, production, and sales, dedicated to providing efficient and energy-saving compressor products. This research will focus on one category of compressor products produced by the enterprise. This type of compressor mainly consists of components such as the casing, crankshaft, and bearing system that provide power transmission, piston-link-cylinder assemblies that execute the refrigeration cycle, motors, and valves. The assembly process is primarily divided into three main phases: assembly, testing, and packaging, encompassing a total of 12 workstations and 32 processes. The specific operating times and their preceding relationships are shown in **Table 1**.

Table 1. Operation working time

Process	Process name	Time(s)	Preceding process
1	Housing cleaning	33.48	-
2	Surface dry	28.76	1
3	Apply a rust-proof coating	42.91	2
4	Press-fit sleeve	19.05	3
5	Install crankshaft bearing	73.57	4
6	Installing sealing ring	13.17	5
7	Bearing fastening	33.86	6
8	Installing connecting rod	65.60	7
9	Piston ring assembly	16.98	8
10	Piston assembly installation	56.08	9
11	Install the cylinder gasket	25.89	3
12	Install the valve	33.97	10,11
13	Valve spring set	39.31	12
14	Installing cylinder head	47.25	10,13
15	Lock the cylinder head nut	26.38	14
16	Motor cavity heating	34.35	7
17	Installing the motor	67.07	15,16
18	Terminal connection	23.51	17
19	Installing motor cover	30.53	18
20	Tighten the motor cover nuts	27.80	19
21	Install the oil pump	54.85	15
22	Install the oil filter	31.43	21
23	Installing the heat sink	24.94	22
24	Install the exhaust valve	34.92	23
25	Install exhaust silencer	26.68	24
26	Installing the bottom cover	44.20	23
27	Lock the bottom cover nut	26.37	26
28	Leak test	25.10	20,25,27
29	performance testing	100.05	28
30	Paste qualified label	26.75	29
31	Finished product packaging	26.13	30
32	Packing and stacking	30.84	31

Among them, certain processes have preceding operations that must be completed before the next process can be carried out. The specific allocation of processes at each workstation and the operation times are shown in **Table 2**.

Table 2. Allocation of processes and operating time for workstation

Workstation	Process assembly	Time(s)
1	1, 2, 3	105.15
2	4, 5, 6, 7	139.65
3	8, 9, 10	138.66
4	11, 12, 13	99.18
5	14, 15	73.63
6	16, 17	101.42
7	18, 19, 20	81.84
8	21, 22, 23	111.21
9	24, 25	61.60
10	26, 27	70.57
11	28, 29	125.15
12	30, 31, 32	83.72

2.2. Analysis of issues

Based on the above data analysis, it was calculated that the current balance rate of the assembly line is 71.1%, with a smoothness index of 47.4. These two indicators indicate that there is significant room for optimization in the assembly line. Therefore, this paper primarily focuses on researching the issue of task allocation. By taking into account the immediate preceding processes, the paper employs algorithms and simulation software to reallocate the current machining processes of compressors in order to improve the assembly situation.

3. Optimization of assembly line balancing based on PSO

3.1. Optimization model

In order to achieve the optimization goals of improving assembly line balance and output, it is necessary to determine the optimization objective function. The optimization objective model established in this paper is as follows:

3.1.1. Assembly rhythm

$$CT = \max(T_i), \quad (i = 1,2,\ldots,m) \tag{1}$$

In the equation: CT represents Cycle Time; T_i denotes the total operation time of all processes at the i-th workstation (i=1,2,...,m).

3.1.2. Smoothness index

$$SI = \sqrt{\frac{\sum_{i=1}^{m}(CT - T_i)^2}{m}} \tag{2}$$

In the equation: *SI* represents Smoothness Index; m refers to the number of workstations.

3.1.3. Objective function

$$minf = w_1 * CT + w_1 * SI \tag{3}$$

In the equation: w_1 and w_2 are weighting coefficients.

3.1.4. Constraints

(1)Ensure that the rearranged processes meet the requirements of the preceding operations.

(2) The same process cannot be assigned to two workstations simultaneously.

(3) All 32 processes must be included in the workstation.

(4) The assembly rhythm must not exceed the maximum operating time of the work elements, that is, $t_i^{max} \leq CT$, (i=1，2⋯，n).

3.2. Design of particle swarm algorithm

(1) Basic PSO algorithm

Particle Swarm Optimization (PSO), proposed by Dr. Eberhart and Dr. Kennedy based on research into the predatory behavior of bird flocks, is a type of swarm intelligence algorithm. It utilizes the sharing of information among individuals within the group to produce an evolutionary process that transitions from disorder to order in the solution space, thereby obtaining an optimal solution. The assembly line studied in this paper is a discrete problem, and the Particle Swarm Optimization algorithm is employed to analyze the assembly line issue, leading to the establishment of the following formula:

$$X_{id}(t+1) = V_{id}(t+1) + X_{id}(t) \tag{4}$$

$$V_{id}(t+1) = \omega V_{id}(t) + c_1 r_1\big(P_{id}(t) - X_{id}(t)\big) + c_2 r_2\big(g_{gd}(t) - X_{id}(t)\big) \tag{5}$$

In this context, *X* represents the position of the particle in the global space, signifying a feasible solution; *V* denotes the running speed of the particle, reflecting the process of global or local optimum learning; *p* indicates the historical optimal position of the current local area; *g* represents the historical optimal position of all particles in the global context; *i* denotes the particle's index (i=1, 2, …, *n*); *d* refers to the dimensions of the particle's position or speed in the global space; t indicates the number of iterations of the particle; *w* is the inertia weight; *r1* and *r2* are arbitrary numbers between [0, 1]; *c1* and *c2* are acceleration factors.

(2) Improvement of PSO algorithm

In traditional particle swarm optimization (PSO) algorithms, the inertia weight *ω* is one of the key factors determining the global and local search capabilities of particles. Typically, *ω* is set as a constant value; when ω is large, the particle has stronger global search capability but weaker local search capability, whereas when ω is small, the particle has weaker global search capability but stronger local search capability.

To enhance the global and local search capabilities of particles at different stages during the iteration process, this paper combines basic PSO with the simulated annealing algorithm. In the optimization process, the simulated annealing algorithm must set an initial temperature to search for the optimal solution based on the objective function. The algorithm randomly generates an initial solution within the solution space of the optimization problem, which serves as the initial solution for the first iteration. It then simulates the cooling process of substances by introducing a random disturbance factor that interferes with the initial solution. The new fitness value is calculated, and the difference between the new fitness value and the original fitness value is obtained. The iteration formula is as follows:

$$P_{ij}^{\theta} = \begin{cases} 1, \ E(j) \leq E(i) \\ e^{-\left(\frac{E(j)-E(i)}{K\theta}\right)} = e^{-\left(\frac{\Delta E}{K\theta}\right)}, \ other \end{cases} \tag{6}$$

In this context, *e* represents the internal energy produced by the object in states *i* and *j*, *ΔE* denotes the change in internal energy, and *K* is the Boltzmann constant. From the equation, it can be observed that when *E(j) < E(i)*, the energy function value of the object also decreases accordingly. If the fitness value calculated in state *j* is lower than that in state *i*, a new solution should be accepted. Conversely, the new solution is selectively accepted. The length of the Markov chain is evaluated through computation to determine whether it can be achieved. If not met, new particles are generated; if the specified length is reached, the termination conditions are observed. This paper establishes that the cycle can terminate when the temperature meets the minimum threshold.

Due to the complexity and number of processes on the assembly line, to reduce algorithmic computation time, the length of the Markov chain is set to 100, with parameters set at 0.8. Once the specified length is reached, it automatically determines whether the temperature condition can be met to exit the process. If the temperature condition is satisfied, it checks whether the iteration count can be met. If the temperature is insufficient, the annealing continues. The temperature is gradually lowered to meet the requirements of annealing, typically using a set annealing rate and following a linear annealing strategy to ensure that particles maintain equilibrium at various temperatures. The formula is as follows:

$$\theta_k = \frac{(\theta_{\square} - \theta_{end}) \times (k_{max} - k)}{k_{max}} + \theta_{end} \tag{7}$$

3.3. Optimization of process allocation based on improved PSO

3.3.1. Model parameter settings

Utilizing MATLAB to reallocate the processes of the compressor assembly line based on an improved Particle Swarm Optimization algorithm, the parameter settings of the algorithm are presented in **Table 3**.

Table 3. Algorithm parameter configuration

Parameter name	Numerical value
Population size	50
Number of iterations	200
Inertia weight	0.7
Learning factor c1	1.5
Learning factor c2	1.5
Initial temperature	1000

The original assembly line comprises 32 processes and a total of 12 workstations. The assembly cycle time has been reduced to 139.65 seconds. The minimum number of workstations for the assembly line can be calculated using the following formula:

$$\text{Min workstations} = \frac{\text{Total Process Time}}{\text{CT}} \approx 9 \tag{8}$$

According to the calculations, the minimum number of workstations for the assembly line is determined to be 9. Therefore, in optimizing the assembly line, the number of workstations is set to 9, 10, and 11. In the assembly line balancing optimization, a fitness evaluation function is constructed to filter the optimal number of workstations. This function takes into account the number of workstations, time equilibrium, and precedence constraints. During the optimization iteration process, the algorithm continuously generates new solutions and evaluates their fitness. Through a simulated annealing mechanism, better solutions are accepted, and ultimately, the solution with the minimum fitness value is selected from the feasible range, determining the optimal number of workstations and the sequence of operations for each optimal workstation. The operational time obtained from the run, along with the workstation's Gantt chart, is illustrated in **Figure 1**.

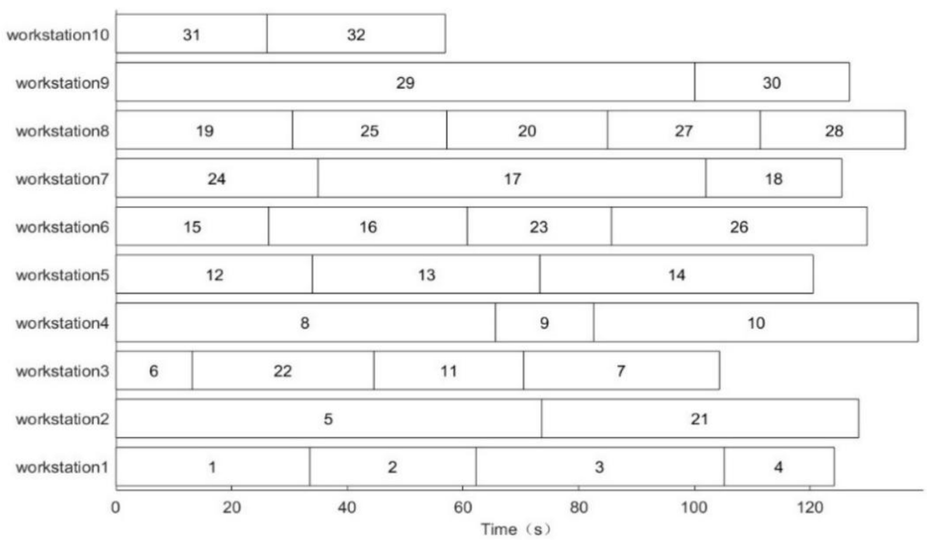


Figure 1. Gantt chart of task duration and workstation

Based on the results obtained from the improved particle swarm optimization algorithm executed in the Matlab program, the optimal number of workstations, the allocation of various processes, the operation times of the workstations, and the computed values of the objective function, including the assembly line balance loss rate and the smoothness index for this allocation method can be deduced. The optimal number of workstations is 10, with the operation times after optimization using the improved particle swarm algorithm being: [Workstation 1 = 124.20s, Workstation 2 = 128.42s, Workstation 3 = 104.35s, Workstation 4 = 138.66s, Workstation 5 = 120.54s, Workstation 6 = 129.87s, Workstation 7 = 125.49s, Workstation 8 = 136.48s, Workstation 9 = 126.80s, Workstation 10 = 56.97s]. Under the allocated condition of these operations, the balance loss rate of the objective function is 14.05%, and the smoothness index is 29.81. Specific details are shown in **Table 4**.

Table 4. Improved process set and operating time

Workstation	Process	Workstation operating time(s)
1	1, 2, 3, 4	124.20
2	5, 21	128.42
3	11, 22, 6, 7	104.35
4	8, 9, 10	138.66
5	12, 13, 14	120.54
6	15, 16, 23, 26	129.87
7	24, 17, 18	125.49
8	19, 27, 20, 25, 28	136.48
9	29, 30	126.80
10	31, 32	56.97
Balance Loss Rate	0.140509	
Smoothing Index	29.814819	

Based on the data above, a mountain accumulation chart has been drawn. It can be observed that after optimizing the improved PSO algorithm, the standard operation times of each workstation have become more balanced compared to before the optimization, as shown in **Figure 2**.

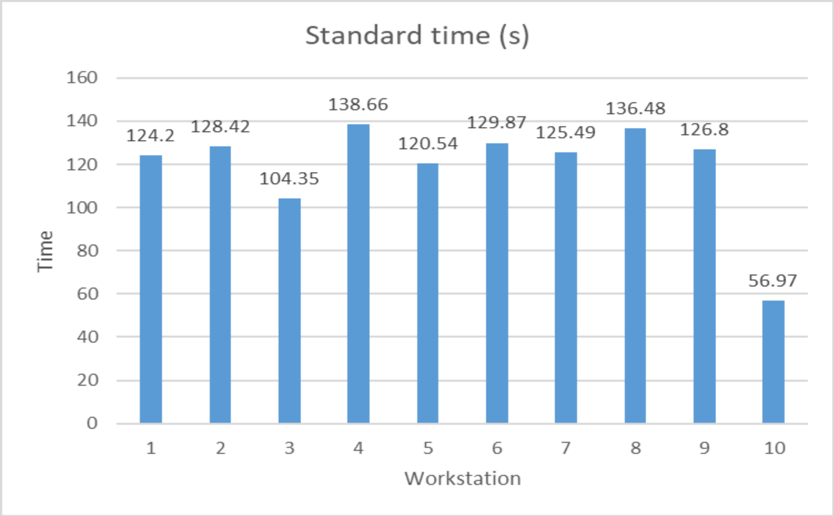


Figure 2. Workstation operation time

4. Assembly line simulation modeling

This article makes the following assumptions when simplifying the system model:

(1) Machines will not experience breakdowns during operation, and the production line will operate continuously.

(2) Each assembly process must be assigned to a workstation.

(3) Each workstation can process at most one product at a time.

(4) The time taken for workers to switch tasks and the transportation time for products are not considered.

(5) The material allocation required for each workstation is sufficient.

Based on **Table 2** and **Table 4**, simulation models before and after optimization are established, and the simulation results are output. A comparison of the data before and after optimization is shown in **Table 5**.

Table 5. Comparison of indicators before and after optimization

Indicator	Before optimization	After optimization
Balance rate	71.1%	85.9%
Balance loss rate	40.6%	14.1%
Assembly cycle time(s)	139.65	138.66
Smoothness index	47.4	29.8
Workstations(Units)	12	10
Utilization rate of workstations	63.7%	84.5%

By analyzing the comparison of various indicators before and after optimization, as detailed in **Table 5**, it can be observed that the production cycle time of the optimized assembly line decreased from 139.65 seconds to 138.66 seconds, the assembly line balance rate improved from 71.1% to 85.9%, the smoothness index decreased from 47.4 to 29.81, the number of workstations was reduced from 12 to 10, and the average utilization rate of workstations increased from 63.7% to 84.5%. Therefore, the balanced state of the optimized assembly line has been significantly enhanced, demonstrating the effectiveness of the optimization plan.

5. Conclusion

This article focuses on the assembly line of a certain company's compressors. Through analysis, it was found that the assembly line suffers from poor balance and unreasonable process arrangements. Subsequently, a mathematical model was constructed based on the assembly line balancing problem, and an improved particle swarm optimization algorithm, specifically a simulated annealing-enhanced particle swarm algorithm, was designed for solution. The model was then solved by incorporating the number of workstations, the process time matrix, and the process priority relationship matrix of the compressor assembly line, yielding an optimal number of workstations as 10. As a result, the balanced rate of the optimized assembly line increased from 63.7% to 85.9%, and the smoothness index decreased to 29.81. The results indicate that combining the improved particle swarm algorithm with Flexsim modeling and simulation as a novel approach to optimize assembly line-related issues can enhance workshop assembly efficiency, increase corporate profits, and provide valuable insights for other similar assembly lines.

Disclosure statement

The author declares no conflict of interest.

References

[1] Yuan KH, Zhang HP, Nan SJ, 2023, Too Big but Not Strong Characteristic and Micro-mechanisms of Digitalization in Chinese Manufacturing Enterprises: Empirical Evidence from Exporting Firms. International Trade Problems, 2023(5): 140–157.

[2] Tripathi V, Chattopadhyaya S, Mukhopadhyay AK, et al., 2022, A Sustainable Methodology Using Lean and Smart Manufacturing for the Cleaner Production of Shop Floor Management in Industry 4.0. Mathematics, 10(3): 347.

[3] Yu HL, He T, 2024, Flexible Production Line Scheduling Method Based on Particle Swarm Optimization Algorithm. Aerospace Manufacturing Technology, 67(6): 84–91.

[4] Xiao H, Zheng QX, 2023, Improved Particle Swarm Optimization Algorithm for the Second Type of Assembly Line Balancing Problem. Journal of Hubei University (Natural Science Edition), 45(2): 164–170.

[5] Yang QM, Liu N, 2024, Optimization of Fuzzy PID Control for Four-Wheel Drive Vehicles Based on Improved Particle Swarm Optimization Algorithm. Chinese Journal of Construction Machinery, 22(6): 744–749.

[6] Luo QY, Jiang DY, Hu XB, et al., 2023, Simulation Optimization of Key Tanning Processes Based on Particle Swarm Optimization Algorithm and Witness. Mechanical Design and Manufacture, 2023(5): 211–214.

[7] Ankita, Sahana SK, 2022, Ba-PSO: A Balanced PSO to Solve Multi-objective Grid Scheduling Problem. Applied Intelligence, 52(4): 4015–4027.

[8] Wang M, Jiang JW, Cao YT, 2022, A Dynamic Target Grasping Control Method for Food Sorting Robot Based on Improved Particle Swarm Optimization. Food & Machinery, 38(3): 86–91.

[9] Zhao B, Wang G, Song JY, et al., 2021, PSO-Algorithm-Based Optimal Design of LCLC Resonant Converters for Space Travelling-Wave Tube Amplifiers Applications. Journal of Electronics & Information Technology, 43(6): 1622–1629.

[10] Shojaie AA, Bariran SES, 2020, Comparison of Two Modified Meta-heuristic Soft Algorithms for Solving a Bi-objective Facility Layout Problem. International Journal of Mathematics in Operational Research, 16(3): 335–345.

[11] Aydoğan EK, Delice Y, Özcan U, et al., 2019, Balancing Stochastic U-lines Using Particle Swarm Optimization. Journal of Intelligent Manufacturing, 30: 97–111.

[12] Yang Z, Liu CG, 2018, Improved Particle Swarm Optimization Algorithm for Multi-objective Fuzzy Scheduling of Shipbuilding Block Production Line. Journal of Ship Science and Technology, 40(9): 46–51.

[13] Liu J, Zhang H, He K, et al., 2018, Multi-objective Particle Swarm Optimization Algorithm Based on Objective Space Division for the Unequal-area Facility Layout Problem. Expert Systems With Applications, 102: 179–192.

[14] Yang B, Chen W, Lin C, et al., 2017, The Algorithm and Simulation of Multi-objective Sequence and Balancing Problem for Mixed Mode Assembly Line. International Journal of Simulation Modeling, 16(2): 357–367.

Integrated Services Platform of International Scientific Cooperation

Innoscience Research (Malaysia), which is global market oriented, was founded in 2016.Innoscience Research focuses on services based on scientific research. By cooperating with universities and scientific institutes all over the world, it performs medical researches to benefit human beings and promotes the interdisciplinary and international exchanges among researchers.

Innoscience Research covers biology, chemistry, physics and many other disciplines. It mainly focuses on the improvement of human health. It aims to promote the cooperation, exploration and exchange among researchers from different countries. By establishing platforms, Innoscience integrates the demands from different fields to realize the combination of clinical research and basic research and to accelerate and deepen the international scientific cooperation.

Cooperation Mode

BIQ-BYWORD
SCIENTIFIC PUBLISHING PTY LTD

Our Journals

The *Journal of Architectural Research and Development* is an international peer-reviewed and open access journal which is devoted to establish a bridge between theory and practice in the fields of architectural and design research, urban planning and built environment research.

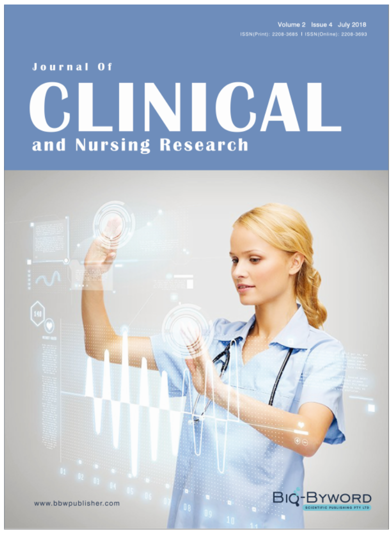
Topics covered but not limited to:

- Architectural design
- Architectural technology, including new technologies and energy saving technologies
- Architectural practice
- Urban planning
- Impacts of architecture on environment

Journal of Clinical and Nursing Research (JCNR) is an international, peer reviewed and open access journal that seeks to promote the development and exchange of knowledge which is directly relevant to all clinical and nursing research and practice. Articles which explore the meaning, prevention, treatment, outcome and impact of a high standard clinical and nursing practice and discipline are encouraged to be submitted as original article, review, case report, short communication and letters.

Topics covered by not limited to:

- Development of clinical and nursing research, evaluation, evidence-based practice and scientific enquiry
- Patients and family experiences of health care
- Clinical and nursing research to enhance patient safety and reduce harm to patients
- Ethics
- Clinical and Nursing history
- Medicine



Journal of Electronic Research and Application is an international, peer-reviewed and open access journal which publishes original articles, reviews, short communications, case studies and letters in the field of electronic research and application.

Topics covered but not limited to:

- Automation
- Circuit Analysis and Application
- Electric and Electronic Measurement Systems
- Electrical Engineering
- Electronic Materials
- Electronics and Communications Engineering
- Power Systems and Power Electronics
- Signal Processing
- Telecommunications Engineering
- Wireless and Mobile Communication