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Hydraulic Sliding Formwork Construction Technology for Main Pier Columns of Highway Bridges

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Abstract: Aiming at the problems of difficulty in balancing construction efficiency and quality, as well as the high safety risks of working at heights during the construction of main piers for highway bridges, this study takes a specific bridge project as an example to introduce the technology of hydraulically sliding formwork for the construction of main piers of highway bridges. An in-depth analysis of the project's construction process found that this technology can effectively improve construction efficiency, ensure the quality of concrete pouring, and significantly reduce the potential safety hazards of working at heights. It provides a reliable technical solution for constructing the main piers of highway bridges and has important reference significance for similar projects.

Keywords: Highway bridges; Main piers; Hydraulic pressure; Sliding; Formwork

Online publication: March 11, 2025

1. Introduction

As a key component of transportation infrastructure, highway bridges play a pivotal role in regional economic development and social exchanges, with their construction quality and efficiency being crucial. The main pier, as the core load-bearing structure of a highway bridge, has a direct impact on the performance, durability, and construction duration of the entire bridge project. In the field of modern bridge construction, as the scale of projects continues to expand and design requirements become increasingly demanding, traditional main pier construction techniques are gradually facing many challenges. Traditional construction methods, such as the full scaffolding method and the formwork turning method, often encounter issues such as cumbersome construction procedures, frequent formwork turnover, high risks of working at heights, and long construction durations when dealing with taller and larger main piers.

These problems not only increase construction costs but also potentially affect the quality and safety of the project. In this context, hydraulically sliding formwork construction technology for highway bridge main piers has emerged. This technology, with its unique advantages, has gradually been applied and promoted in many bridge projects. The hydraulically sliding formwork construction technology enables simultaneous concrete pouring and formwork lifting, reducing construction intervals and significantly improving efficiency. Through an automated hydraulic lifting system, the rising speed and position of the formwork can be precisely controlled, effectively ensuring the verticality and cross-sectional dimensional accuracy of the main pier, and improving the pouring quality and appearance of flatness of the concrete. Based on this, this article studies the technological process of hydraulically sliding formwork construction technology.

2. Project overview

A certain bridge serves as a key transportation node connecting the new urban area and the old city. The main bridge adopts a prestressed concrete continuous rigid frame bridge type, with a total length of 1,200 m and a main span of 200 m. There are 4 main pier columns, with designed heights ranging from 50 m to 80 m, and the tallest main pier column reaches 80 m. The main pier columns have rectangular cross-sections, with dimensions of 6 m in length and 4 m in width. The designed concrete strength grade is C50, and the concrete pouring volume for a single main pier column is approximately 1,200 m^3. The geological conditions of the project site are complex, with the upper stratum mainly consisting of silty clay and the lower stratum being sandstone. The groundwater level is located 10 m below the surface. The surrounding environment of the construction site is relatively special, with one side adjacent to an existing railway line and a narrow construction site, posing extremely high requirements for construction organization and safety protection [1].

3. Composition of the hydraulic sliding formwork system

3.1. Formwork system

The formwork system is crafted from high-quality Q235 steel, with a panel thickness set at 6 mm to ensure the strength and durability of the formwork. The height of the formwork is carefully designed to be 1.5 m, accommodating various needs during the construction process. To further enhance the overall stability and rigidity of the formwork, the back ridge section utilizes 10# channel steel, evenly arranged at intervals of 350 mm, effectively increasing the formwork's load-bearing capacity. Connections between the formwork panels are secured using M18 high-strength bolts, positioned at intervals of 200 mm along the edges of the formwork and 400 mm in the central part, ensuring tight connections. The width of the seams is strictly controlled within 1.5 mm to eliminate any gaps that could potentially affect the quality of the concrete [2]. Additionally, a layer of specialized release agent is uniformly applied to the inner side of the formwork, with a thickness of approximately 0.15 mm. This release agent not only effectively protects the surface of the formwork but also ensures that the concrete exhibits a smooth and clean surface after demolding.

3.2. Hydraulic lifting system

The hydraulic lifting system consists of three core components: hydraulic jacks, a hydraulic control console, and oil lines. For this project, YKT-50 hydraulic jacks with a rated lifting capacity of up to 5 tons were chosen, adequate for various challenges during construction. A total of 24 jacks are evenly distributed around the main pier column, with a horizontal spacing of approximately 1.8 m between adjacent jacks, ensuring stable and uniform lifting. The ZKT-60 hydraulic control console, featuring precise pressure control and travel display with a pressure control accuracy of 0.4 MPa, provides intuitive and accurate operational guidance for construction workers. The oil lines are connected using high-pressure seamless steel pipes with an inner diameter of 12 mm and a total length of approximately 400 m. Through reasonable oil line arrangement and precise oil supply control, each jack receives a uniform and stable pressure during the lifting process, achieving the goal of synchronous lifting [3].

3.3. Operating platform design

The operating platform is an essential auxiliary facility during construction, consisting of a main operating platform, an upper auxiliary platform, and inner and outer hanging scaffolds. The main operating platform adopts a sturdy truss structure welded with 12# angle steel, covering an area of approximately 80 m^2 and designed with a carrying capacity of up to 3 kN/m^2, adequate for construction workers, equipment, and some materials. The upper auxiliary platform, located 2 m above the main operating platform and covering an area of approximately 40 m^2, is primarily used for reinforcing bar extension and initial binding, providing a more spacious and convenient operating space for construction workers [4]. The inner and outer hanging scaffolds, made of 48 mm diameter steel pipes with a width of 0.8 m, are suspended below the main operating platform and adjusted using manual hoists. These scaffolds not only facilitate formwork cleaning and maintenance but also aid in the finishing and curing of the concrete surface, ensuring improved construction quality and efficiency.

4. Technological process of hydraulic sliding formwork construction technology for main pier columns of highway bridges

4.1. Preliminary preparation

Before construction, conduct a detailed survey of the construction site, build access roads, and widen and level the site to ensure smooth passage for construction vehicles and machinery. Purchase raw materials such as steel bars, cement, and sand that meet quality standards according to engineering design requirements, and conduct strict inspections. Among them, the yield strength, tensile strength, and other indicators of steel bars must comply with relevant steel standards, and the stability, strength, and other indicators of cement must meet the cement standard values. Comprehensively inspect, debug, and pre-assemble various components of the hydraulic sliding formwork system. Conduct a simulated sliding test at the assembly site to ensure stable and reliable system operation. Organize construction workers to conduct technical clarification and safety training to familiarize them with construction techniques, operating procedures, and safety precautions. Workers can only start working after passing the assessment. After completing the foundation construction of the main pier column and achieving the designed strength, use a total station instrument for precise surveying and setting out to determine the center position and outline of the main pier column. Set stable control points on the top surface of the foundation for measurement, monitoring, and correction during the construction process [5].

4.2. Steel bar binding

The processing and fabrication of steel bars are centralized in a dedicated processing field. According to the detailed requirements of the design drawings, the steel bars are precisely processed into various specifications of semi-finished products. In the construction of the main pier column, HRB400 grade threaded steel with a diameter of 32 mm is selected for the vertical steel bars, and the arrangement spacing is set to 250 mm to ensure the strength and stability of the structure [6]. HRB335 grade steel bars with a diameter of 14 mm are selected for the horizontal hoops, and the arrangement spacing is 200 mm, which further strengthens the integrity and shear resistance of the structure. The connection method of steel bars adopts advanced straight thread sleeve connection technology, which is not only high in strength but also convenient for construction. To ensure the safety and reliability of the structure, the number of steel bar joints in the same section is strictly controlled within 50% of the total number of steel bars, effectively avoiding potential hazards that may arise from too many joints. During the steel bar binding process, operators use the operating platform, positioning bars, and binding wires to accurately fix the position of the steel bars, ensuring that the spacing and protective layer thickness of the steel bars strictly comply with the design requirements. To precisely control the thickness of the protective layer, special 55 mm thick concrete spacers are used. These spacers are arranged in a quincunx pattern with a spacing of 1.2 m, effectively preventing the steel bars from directly contacting the formwork and ensuring the accuracy of the steel bar position and the construction quality of the concrete.

4.3. Formwork installation and debugging

The pre-assembled formwork is safely and precisely lifted to the top surface of the main pier column foundation and installed based on the accurately measured setting-out position. During installation, technicians use theodolites and level gauges to monitor the verticality and levelness of the formwork in real-time, ensuring that the verticality deviation is controlled within 1/1000 and the levelness deviation does not exceed 6 mm to meet the construction accuracy requirements. After the formwork installation is completed, the debugging work of the hydraulic lifting system begins immediately. During debugging, professionals carefully check the connections between the jacks, hydraulic control console, and oil pipes for tightness and leak-free conditions, ensuring the system's safety and reliability. Subsequently, a no-load test run is conducted to observe the stability and synchronicity of the jack's lifting and lowering, as well as the accuracy of the pressure display and stroke control on the hydraulic control console. Any issues identified during the debugging process are immediately rectified to ensure that the hydraulic sliding formwork system operates normally and stably, providing solid and reliable support for subsequent concrete pouring and sliding operations [7].

4.4. Concrete pouring

In the concrete pouring process, an HZS120 concrete mixing plant is used for centralized mixing to ensure precise concrete proportions and stable quality. The concrete ingredients strictly follow the designed ratio of cement, sand, stones, water, and additives, which is 1:2.5:3.8:0.48:0.03. This ratio is carefully calculated to meet the project's various performance indicators. The slump of the concrete is strictly controlled within the range of 150–180 mm to ensure good workability and pouring quality. Concrete transportation relies on 10 m^3 capacity mixing trucks, which maintain continuous rotation of the tank during transportation to effectively prevent concrete segregation and ensure the quality and performance of the concrete during pouring. The pouring operation adopts a layered pouring method, with each layer's thickness precisely controlled at around 350 mm to ensure uniform distribution and compactness of the concrete. During pouring, the concrete is evenly distributed from the center of the main pier column to the surrounding area, ensuring uniform concrete distribution across the entire pouring area without obvious voids or bubbles. To further improve the compactness and strength of the concrete, a 50-type insertion-type vibrating rod is used for vibration. The vibrating rod is inserted into the lower layer of concrete with a depth of not less than 60 mm, and the vibration time is controlled between 20–30 seconds until the concrete surface no longer sinks, no bubbles emerge, and the surface is covered with a layer of cement paste, indicating that the desired vibration effect has been achieved [8]. Additionally, throughout the entire concrete pouring process, dedicated personnel are responsible for monitoring the working status of the formwork, steel bars, and the hydraulic sliding formwork system. If any abnormalities are detected, such as formwork deformation, steel bar displacement, or failures in the hydraulic sliding formwork system, the pouring operation is immediately stopped. The cause is investigated, and appropriate measures are taken to address the issue, ensuring the safety and quality of the construction.

4.5. Hydraulic climbing

The initial climbing operation can be started when the concrete is poured to about 70% of the formwork height and the concrete strength reaches 0.3–0.5 MPa. The height of the initial climb is strictly controlled to around 60 mm, with the main purpose of observing the strength of the concrete exiting the mold and the working status of the climbing system. During the initial climbing process, close attention is paid to the slump of the concrete and the ease of climbing. Once abnormalities such as concrete slump or difficulty in climbing are found, the mix proportion of the concrete or climbing parameters is immediately adjusted to ensure smooth climbing [9]. After the initial climb is normal, it can be transferred to the normal climbing stage. The speed of normal climbing is comprehensively determined based on factors such as the setting time of the concrete, temperature conditions, and construction process requirements, and is generally controlled between 250–350 mm/h. During the climbing process, the hydraulic control panel is used to synchronously control the jacks, ensuring that the travel difference between each jack does not exceed 15 mm, to ensure stable and uniform climbing. To ensure the accuracy of the verticality, cross-sectional dimensions, and axis position of the main pier, a total station is used to perform a measurement check every 1.5 m of climbing. If deviations exceed the allowable range, measures are immediately taken to correct them, such as adjusting the climbing height of the jacks or setting wedges between the formwork and the concrete, to ensure that the accuracy and quality of the main pier meet the design requirements.

4.6. Formwork cleaning and maintenance

After each hydraulic climb, the surface of the formwork is promptly cleaned. A scraper and steel wire brush is used to remove concrete, mortar, and debris adhered to the surface of the formwork, which is then rinsed clean with a high-pressure water gun. At the same time, the connecting bolts, welds, and back ribs of the formwork are inspected. If there is any loosening, deformation, or damage, they are promptly tightened, repaired, or replaced. The hydraulic lifting system, including jacks, oil pipes, and the hydraulic control panel, is inspected and maintained. The sealing performance of the jacks, the connection of the oil pipes, and the operating parameters of the hydraulic control panel are checked to ensure that the hydraulic lifting system performs well and operates reliably. Regular inspections are conducted on the operating platform, internal and external hanging brackets, etc., to check the stability of the platform structure, the flexibility of the hanging brackets, and the integrity of safety protection facilities. Any potential safety hazards are promptly eliminated to ensure the safety of construction workers [10].

5. Conclusion

The application of hydraulic climbing formwork technology for highway bridge main piers in the "Guangming Bridge" project has achieved good results. Through this technology, the construction efficiency of the main piers has been significantly improved, and the construction period has been reduced by about 35% compared to traditional construction methods. At the same time, it has effectively ensured the construction quality of the main piers, with a one-time qualification rate of concrete strength of over 99%. The appearance quality of the main piers is smooth and flat, with no obvious defects. In terms of construction safety, the risk of working at heights has been reduced by reasonably setting up operating platforms and safety protection facilities, resulting in a significant reduction in the incidence of safety accidents. However, in the actual construction process, attention still needs to be paid to issues such as oil temperature control in the hydraulic system and wear monitoring of the formwork. With the continuous development of technology and the accumulation of construction experience, the hydraulic climbing formwork technology for highway bridge main piers will continue to improve, providing stronger technical support for the construction of highway bridges.

Disclosure statement

The author declares no conflict of interest.

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Pagoda as Grottos: Rethinking the Architectural Form of Cave 4 of Maijishan Grottoes

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Abstract: This paper mainly explores the architectural form of the interior of Maiji Mountain's Cave 4 and the spiritual realm it establishes. Previous research holds the view that the niche within Cave 4 is architecturally modeled after a tent-like structure. However, after in-depth research, this paper suggests that the niche in Cave 4 is more of an imitation of an embedded stupa, or rather, it reconstructs the stupa in an embedded form within the cave. In prior studies, analysis historical background and architectural details of Cave 4 remains inadequate, thus, this paper aims to take a thorough investigation on this point, and further clarify the significance of the form of the Buddha niche in Cave 4, as well as its construction design origins. Specifically, the octagonal wooden-imitating column, lotus-shaped clamp, inverted lotus pedestal, five lotus petals, and shadow sculptures within the niche, the shallow-relief ceiling and small platform outside the niche, as well as the banana leaf decorations, all suggest that the architectural form Cave 4 imitates is likely a single-story wooden stupa. In this way, the connection that this embedded stupa creates between the Budda and the faithful, is more direct and intimate, especially compared to the one built in traditional Buddhist activities. Moreover, by coordinating with various visual materials inside the cave, such as the layout of the Dharma assembly and the exquisite details of the Buddha images, it reconstructs the "realm of the mind" in Buddhism, reinforcing the faithful's dual experience both in physical and spiritual fields. The Master Teacher Studio of basic education came into being with the new curriculum reform, which has become a new mechanism for the construction of teaching staff in social situations in China. As a brand-new way in the construction of teaching staff in the new era, through reviewing the relevant research, it is found that the focus of academic circles on Master Teacher Studio is mainly in four aspects: clarifying the conceptual boundary, seeking theoretical support, defining the functional orientation, and exploring status quo of development. The exploration of the research process is not only a process of summary but also a process of reflection. By reviewing relevant research, reflecting on the problems that have appeared in the process of building the Master Teacher Studio in basic education, clarify the development path of the Master Teacher Studio and further affirm its advantages to the construction of teaching staff in the Chinese context.

Keywords: Fourth grotto of Maiji Mountain; Four-gabled pyramid roof structure; Pagoda; One-floor wooden pagoda; Embedded pagoda; Grotto as pagoda; Topography of mind

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1. Introduction

Maijishan Grottoes is located in Qin State, where Tianshui, Gansu province is nowadays. The mountain is named by its unique, wheat, stack-like shape. The Grottoes has 221 caves and niches. Cave 4 was first recorded in an inscription by Xin Yu. It was sponsored by Yunxin Li, the grand commander of Qin State, to commemorate his father's death. The construction of Cave 4 was approximately from 570 B.C.E. to 574 B.C.E. [1]. In February 2024, after a field study in Maijishan Grottoes, the author found that the origin of the design of niches in Cave 4 was yet not a consensus between researchers.

The researchers studying Dunhuang Research and Architecture believe that the seven niches of Cave 4 imitate Dou Zhang, an ancient tent-like piece of furniture. Mo Xiao pointed out that the architectural form of Cave 4 imitates a tent [2]. He further concluded, based on the description of Dou Zhang in Shiming by Xi Liu, an author from the Han dynasty, that Cave 4 imitates Dou Zhang. Xinian Fu believes that Cave 4 imitates Buddha's Tent. He, however, equates Buddha's Tent with Dou Zhang in his description and believes that Buddha's Tent consisted of elements of Dou Zhang and drapery [3]. Researchers, like Jie Wang, Guangqiang Dong, and Yuexin Chen follow the theory of imitating Dou Zhang in their study and some classify Cave 4 based on this hypothesis.

Chunyang Dai, however, proposes a different perspective in his study. He observed the evident difference in thickness between columns in Cave 4 and the excavated rods of tents from Southern and Northern Dynasties. He then pointed out that Cave 4 more likely imitates wooden architecture [4].

The author noticed that the theory of imitating Dou Zhang, proposed by both Xiao and Fu, has deficient evidence. Admittedly, the architectural form of Cave 4 is similar to Dou Zhang, but the similarity could also be led by the two objects that imitate the same subject. Furthermore, considering the formality and authority of Cave 4 as a Buddhist architecture, it is less possible that it imitates Dou Zhang, a temporary structure. Henceforth, it is improper to directly equate Cave 4 with Dou Zhang.

2. Doubts about the theory of imitating Dou Zhang

The theory of imitating Dou Zhang is based on the similarity of form between the objects. However, three clear doubts remain. Firstly, Cave 4, as a Buddhist architecture, is unlikely to imitate Dou Zhang as a secular object. Secondly, the formal and authoritative architectural structures in Cave 4 are largely different from Dou Zhang as a common daily use. Thirdly, at the time it was constructed, no evident pagodas existed in and around Cave 4. The second part of the paper will focus on elaborate analysis of these three doubts.

2.1. Drapery on the exterior of niches is not a tent despite their similarity

Dai classified the tent into three distinct categories: the canopy tent, Dou Zhang, and the sleeping tent [4,16,17]. Considering the architectural design logic, the seven niches are the core of the cave and are connected with the hip roof hall, which means it is unlikely to use the informal elements of a sleeping tent. Each of the seven niches has nine statues, including one Buddha, two disciples, and six Bodhisattvas. All statues together constitute the scenery of the Buddha preaching the Dharma.

Furthermore, the theme that the niches express is also not consistent with the application scenario of sleeping tents in daily life. Dou Zhang, designed to be a convenient resting space during trips, is mainly for secular daily use [4]. Cave 4 is a formal and authoritative space. It includes religious figures like Buddhas and Bodhisattvas and is led and protected by the Thousand Buddha Corridor and hip roof. The designers were unlikely to place Dou Zhang, a daily use, in the center of the interior of the whole space they worship.

Cave 4 is unlikely to imitate the tents used by nomadic people as well. The design of the square body and the pyramidal roof in Cave 4 is different from the form of the design of nomadic tents in Northern and Western China. The latter, usually being yurts, have quite a distinct round body and cone-shaped roof. Emperor Xiaowen of Northern Wei led the royal family to popularize the Han culture and Buddhism. The trend of nomadic style is not found in the other Grottoes created in the late Southern and Northern Dynasties either. Henceforth, Cave 4 is unlikely to imitate the nomadic tent.

Among the three categories of tents, the canopy tent is the most formal. Yucai Duan notes in The Rites of Zhou that "The canopy tent has beams and pillars that can be moved" [5]. From his note, it is evident that the canopy tent is also a portable, temporary tent-like Dou Zhang, though it has a greater formality. As furniture for daily use, both Dou Zhang and bed-curtain are unlikely to be juxtaposed with architectural elements like the hip roof in Cave 4.

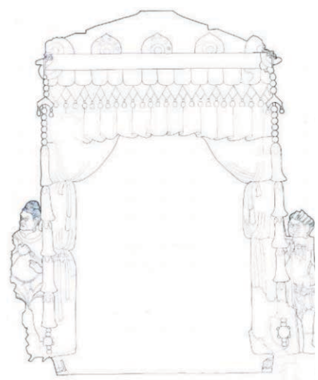
Since the Qin and Han Dynasties China has developed the tradition of decorating palaces and high-end architecture with drapery. "The giant bed-curtain—'the canopy tent,' is 'the tent of the king,'...originated from a palace architecture—the courtyard house" [4,16].

Being decorated by the canopy tent-like drapery on the exterior does not necessarily mean that the architectural form of the niche itself is a tent. For instance, Notes to Luoyang Buddhist Temple writes: "The wooden structures were decorated with silks and fabrics, and the wall was colored in a reddish hue" [6].

This is a typical description of how wooden architecture in Buddhist temples were decorated with luxurious fabrics. People in central China started to decorate palaces with drapery in the Qin and Han Dynasties. Considering the record in Buddhist monographs, it is highly possible that important palaces and Buddhist architectures were still decorated with drapery in the late Northern Dynasty.

The existence of drapery decorations in ancient Buddhist architecture could also be proven by relics. The top of the tenth stele in niches at the North Wall of Tian Tong Cave and Cave 133 No.10, Maijishan Grottoes depicts a wooden architecture with a hip roof, which is decorated with elaborate drapery. The time Cave 4 was created is close to the time Notes to Luoyang Buddhist Temple was written. The drapery relief on the exterior of the niches in Cave 4 could also intend to be a company with a kind of wooden architecture.

Table 1. Comparison between drapery decorated Buddhist architecture from the Northern Zhou Dynasty and the Western Wei Dynasty

Grottoes	Drapery on statue tablet in Cave 133, Maijishan Grottoes, Western Wei Dynasty [7]	Drapery on the exterior of niches in Cave 4, Maijishan Grottoes, Northern Zhou Dynasty [8]
Pattern of drapery		

Henceforth, the author hypothesizes that Cave 4 might imitate an important Buddhist wooden architecture from the late Northern Wei Dynasty, rather than imitating the sleeping tent, Dou Zhang, the canopy tent, and nomadic tents.

2.2. The architectural logical mismatch of niches as the heart of the cave and the temporality of Dou Zhang

Researchers widely recognize that niches in Cave 4 imitate the look and structure of Dou Zhang after the late Northern Wei Dynasty. From the perspective of architectural logic, however, Buddhist architecture is not likely to imitate Dou Zhang which has a temporary use. Furthermore, as a daily use, Dou Zhang does not match the high status of the hip roof as a common element of the royal palace.

Dou Zhang is a seated canopy, widely used by the emperor, officers, and the general public [4,17]. Xinian Fu proposes that Cave 3 could be the corridor towards Cave 4 before it got corrupted. It has stone reliefs of thousand Buddhas and stone walls, which is similar to Cave 168. It is also widely known that Cave 3 and Cave 4 were constructed in the same period [9].

The Thousand Buddha Corridor in Cave 3 and the hip roof hall of Cave 4 together create a lead-in to Cave 4. From the perspective of worshippers, who experienced the whole space, the massive lead-in created by the corridor and the hip roof hall implies the importance of the elements behind them. The hip roof hall, hidden behind Cave 3, is an important component of the whole system, while the niches behind the hall are the heart of the caves.

The application of the hip roof represents the highest status in the system of ancient Chinese architecture and usually appears in the main hall of royal palaces and temples. The Buddha Hall of Cave 4 applies a permanent and high-status form and includes a hip roof, seven bays, and eight columns. The tents, however, usually represent temporality. The designers had no reason to lead the audience to Dou Zhang, a temporary daily use, with architectures of the highest status.

Henceforth, the author believes that the high-status elements of Cave 4, including the elaborate Thousand Buddha Corridor and the hip roof Buddha Hall, are more reasonable to lead the audience to a high-status Buddhist architecture with drapery decoration and form an architectural system consistent in status and purpose.

2.3. The mismatch of the eastward evolution progress of the pagoda and the missing pagoda during the creation of Cave 4

Throughout the development of Buddhism, pagodas have always been the heart of temples from the Eastern Han Dynasty to the Tang Dynasty. In the early Northern Wei Dynasty, the center pillar was still the core element of Grottoes.

Pagoda, the symbol of Shakyamuni, is of high standing in Buddhist worship. In ritual, it is also the center of contemplation, prayer, and chanting for early Buddhists. Circumambulation around pagodas is the key ritual in early Buddhism. At the time, Buddhists believed pagodas to be of supreme importance and irreplaceable in their belief. Pagodas had always been the center of temples and were widely built by Buddhists since Ashoka converted to Buddhism, to the transmission of Buddhism in China from the Eastern Han Dynasty to the Northern Wei Dynasty. Both pagodas in Yongning Temple and Songyue Temple are in the center of the temple they belong to. Pagodas were still one of the central architectures in these temples until the Tang Dynasty. The greatest pagodas created in the Tang Dynasty, including Great Wild Goose Pagoda, Small Wild Goose Pagoda, and the pagoda in Huayan Monastery, are all located in the center of the temples' plans.

Considering the location of Maijishan Grottoes as the place of worship and of famous monks like Xuangao practiced Buddhism, sponsors and major designers of Cave 4 could barely ignore the pagoda in composition [6]. No records mention that the designers used the body of the pyramidal-like mountain as a symbol of the pagoda either.

Ignoring the pagoda in the design of Cave 4 is unreasonable, for the architecture was the heart of Buddhist worship at the time Cave 4 was created. Considering the importance of pagodas and the development of Buddhism in the Northern Zhou Dynasty, the pagoda might be added in another unique form despite its seeming absence in Cave 4.

In the early transmission of Buddhism in China, the pagodas were mainly mchod-rten, the center pillar pagodas, and pavilion-style pagodas. Considering the imitation of the wooden structure in Cave 4, the hidden pagoda in Cave 4 might be a pseudo-timber structural pavilion-style pagoda.

3. The similarity between the niches of Cave 4 and the pseudo-timber structural pagodas before late Southern and Northern Dynasties

The similarity between Cave 4 and the existing wooden pavilion-style pagodas must be recognized if Cave 4 imitates the designs of these wooden pavilion-style pagodas.

The existing pavilion-style pagodas created from the Western Han Dynasty to the late Southern and Northern Dynasties includes: the stone-carved pseudo-timber structural Buddha pagoda sponsored by Cao Tiandu in Shuozhou, Shanxi, originally built in the first year of the Tian'an era of the Northern Wei Dynasty (466 AD), the Xiuding Temple Pagoda in Anyang, Henan, which was originally built in the 18th year of the Taihe era of the Northern Wei Dynasty (494 AD) and was rebuilt during the Tang Dynasty, the nine-story wooden pagoda of Yongning Temple in Luoyang, Henan, built in the first year of the Xiping era of the Northern Wei Dynasty (516 AD), the nine-story stone-carved pseudo-timber structural pagoda at the Yungang Grottoes in Datong, Shanxi, which dates from 386 to 534 AD, the three-story pseudo-timber structural pagoda on the west wall of the main chamber of Cave 14 at the Yungang Grottoes in Datong, Shanxi, from the Northern Wei Dynasty (386–494 AD), and the three-story Northern Wei pagoda in the Jataka of Vessantara mural at Cave 254 of the Mogao Grottoes in Dunhuang, Gansu, from the Northern Wei period. These preserved pagodas have several similarities with the architectural form of Cave 4. The comparison is shown in the table below.

Table 2. Comparison of characteristics of architectural forms between pavilion-style pagodas from the Han Dynasty to Southern and Northern Dynasties and Cave 4 at Maijishan Grottoes

Comparison of characteristics	Pavilion-style pagodas from the Han Dynasty to the Southern and Northern Dynasties	Cave 4, Maijishan Grottoes
Shape of body	Mostly with square body	square body niches
Number of story	Mainly with odd numbers of stories, such as single-story, three-story, five-story, seven-story, or nine-story pagodas	Single-story niches
Pseudo-timber structure	Mostly pseudo-timber structure pagodas	Pseudo-timber structure style
roof	Mostly pyramidal roof	Pyramidal roof

The comparison shows that there are four evident similarities between the architectural form of niches in

Cave 4 and the existing pseudo-timber structural pagoda: the square body, the odd number story, the imitation of the wooden structure, and the top of the pyramidal roof. The similarities lead to reconsidering the relationship between Grottoes and pagodas. The author believes that Cave 4 may imitate the single-story square wooden pavilion-style pagoda.

The Xi'an Museum has several collections of existing steles of niches created in the Northern Zhou Dynasty, most of them decorated with drapery. In the Kangxi Dictionary, one of the meanings of the character of niche is pagoda or the room under pagoda. In **Figure 1**, the museum also preserves a pavilion-style pagoda from the Northern Wei Dynasty, which has a square body, drapery decoration, imitation of octagonal wooden columns, and a top that looks like a hip roof or pyramidal roof. In **Figure 2**, the case is quite similar to the architectural form of Cave 4. It is highly possible for these steles of niches to be imitations of the pagodas with drapery created in the Northern Zhou Dynasty.

Figure 1. The statue tablet of Buddhist niche from the Northern Zhou Dynasty (Source: Xi'an Museum)

Figure 2. The pavilion-style statue pagoda from the Northern Wei Dynasty (Source: Xi'an Museum)

The steles of pagodas created in the Northern Wei Dynasty, excavated in Xi'an also support the hypothesis that Cave 4 imitates the single-story wooden pagoda with drapery.

4. Pagoda as Grottoes: a hypothesis to the origin of the architectural form of the niches

Although Cave 4 does not follow the common sense of Buddhist architectural design and has no evident central pillar or pagoda, its form is similar to that of the pavilion-style pagodas, created during and before the Southern and Northern Dynasties. Some characteristics of pagodas might be preserved in Grottoes.

Sicheng Liang points out that the common form of the Chinese wooden pagoda was formed in the Southern and Northern Dynasties after being transmitted to China. It is a pity that none of the cases are preserved in China, but the Kofukuji five-story pagoda, the center pillar in the caves of Yungang Grottoes, and pagodas in murals in Mogao Grottoes all can represent this kind of pagoda. Another important clue is that all pagodas created between the Wei Dynasty and Kaiyuan and Tianbao era in the Tang Dynasty—except Songyue Temple—have square bodies [10].

Based on Liang's research and the existing pagodas created before the Northern Dynasty, the author hypothesizes that the wooden pavilion-style pagoda with the square body was once a major form of pagodas in the late Southern and Northern Dynasties. The Songyue Pagoda's body reliefs, the independent single-story pagoda behind the Songyue Pagoda from the Northern Wei Dynasty, the stone-carved single-layer pagoda in the Great Buddha Cave of Xiangtangshan from the Northern Qi Dynasty, as well as those found in the Subashi Great Buddha Temple in Xinjiang, Maulsari Temple Ruins, Rawak Buddha Temple in Lop County, and the single-story pagodas seen on the walls of Yungang Grottoes and Tianlongshan reliefs, all prove that the single-story pagoda has existed widely in and before the late Northern Zhou Dynasty. The funerary function of the single-story pagodas may have continued from the parinirvana of Shakyamuni until after the Tang Dynasty. Yunxin Li, in memory of his father, adopted the architectural form of a single-story pagoda in Cave 4, which aligns with this Buddhist tradition. Thus, the design of the niches in Cave 4 is likely to imitate a single-story wooden pagoda, decorated with curtains, rather than a dugong structure.

Why does Cave 4 not have an evident appearance of a pagoda? Considering that the earliest Western Wei Grottoes at Maijishan were influenced by the construction of Yungang and Longmen Grottoes. Before the relocation of the Northern Wei capital, Yungang Grottoes achieved the innovation of separating the main Buddha statue from the pagoda; the Binyang Central Cave at the Longmen Grottoes makes evident the disappearance of the main pagoda, shifting the focus from worshipping the pagoda to prostrating before the main Buddha statue. The designers of the cave temples attempted to represent the top of the pagoda with a lotus at the top, subtly implying that the cave is the pagoda to the believers. This idea may have not only influenced the Grottoes around Longmen Grottoes but also extended westward to influence the Mogao Grottoes and Maijishan Grottoes. Cave 4 likely achieved the effect of a pagoda as a grotto through the architectural elements and details of a single-story wooden pagoda.

5. Pagodas as the heart of Buddhist culture

During the eastward transmission of the pagoda from India, the initial form of the open-air stupa in India evolved into various forms in China's Western Regions, including the open-air stupa, the central pillar-style pagoda within Grottoes, and the sinicized multi-storied pagoda. From the early Northern Wei period and before, up to the Kaiyuan Tianbao era of the Tang Dynasty, pagodas, as symbols of Shakyamuni, consistently occupied the central position in Buddhist temples.

The author previously questioned the absence of an evident pagoda in Cave 4 of Maijishan. This problem was resolved under the premise that Cave 4 mimics a single-story wooden pagoda: the seven Buddha niches in Cave 4 have already served the function and significance of an embedded pagoda, thus eliminating the need for an additional one.

As previously stated, the importance and rank of Dou Zhang and the hip roof do not match, and the temporary nature of the canopy tent is also incompatible with the permanence of the hip roof. However, the high status and permanent nature of the pagoda and hip roof are perfectly aligned. The Thousand Buddha Corridor and the hip roof in Cave 3 serve as a prelude, leading to the core of Cave 4's architectural complex—the most important building in Buddhism—the pagoda, whose significance justifies the placement of the hip roof at the forefront. The purpose of constructing the hip roof is to highlight the importance and high rank of the embedded pagoda. This arrangement of hierarchy and sequence is consistent with Buddhist and architectural logic and explains the grand approach of the architectural lead-in.

Therefore, the embedded pagoda within the niches of Cave 4, which mimics a single-story wooden pagoda, is likely the fundamental reason and purpose for the construction of the grand hip roof. Only a pagoda deserves such an exalted status. The embedded pagoda within the niches of Cave 4—serving as the pagoda within the cave—enjoys a central position within the architectural complex of Cave 4.

6. The effect of grottoes as pagodas in mind topography

The design of the embedded pagoda significantly enhances the devotees' inner veneration of the Buddha and their resonance with the topography of the mind, marking a significant innovation in Buddhist architecture. The embedded pagoda realizes the concept of pagodas as grottoes, further practicing the belief that the cave itself could represent a pagoda. During the Northern Wei Dynasty, Mahayana Buddhism began to worship colossal Buddha statues, leading to the innovation in the Binyang Middle Cave at Longmen Grottoes, where a large lotus at the top replaced the central pillar pagoda to represent the top; in the Mogao Grottoes, the domed ceiling replaced the central pillar pagoda to represent the top, and at Maijishan, the pyramidal roof with five lotus carvings also represented the top of the wooden pagoda.

This concept may have originated from the Yungang and Longmen Grottoes and influenced the surrounding Grottoes, as well as the Mogao Grottoes and Maijishan Grottoes. In this phase, the pagoda's disappearance facilitated the realization of the design philosophy that the cave is the pagoda, leading to a flourishing of diverse interpretations. The architectural language of different pagoda tops explained the embedded pagoda design concept of the pagoda as grottoes to the devotees, thereby achieving the concept that the cave is the pagoda.

Compared to the distant traditional circumambulation around the pagoda, the design of the pagoda as a grotto allows devotees to be within the pagoda, venerating the Buddhas such as Shakyamuni and the Seven Buddhas as close as possible. Through exquisite, thin, sculpted murals with life-like details, the iconographic layout of one Buddha, two disciples and six bodhisattvas, the symbolic design of the embedded pagoda, the exquisite craftsmanship of decorative curtains, the existing main Buddha and bodhisattva mudras within the cave, and the scenes of flying apsaras and deities attending gatherings in the murals inside and outside the cave, the designers and craftsmen of Cave 4 collectively depicted the domain of the Seven Buddhas' teachings or Shakyamuni's seven teachings. This promotes spiritual and mental communication between the devotees and the Buddha in the same space. The design has a psychological impact on the devotees that far exceeds the traditional form of circumambulation, bringing them closer to the divine, and achieving a powerful reconstruction of the mind topography.

Through its architectural language, unlike traditional outdoor stupas, cave central pillar pagodas, and ordinary multi-story pagodas, the embedded pagoda conveys the message that "the cave is the pagoda" and "the devotees are with the Buddha." This started a new phase in Buddhist architecture. The design allows devotees to communicate with the Buddha within the pagoda, which is of great significance.

At the end of the Northern Zhou Dynasty, Buddhist architectural designers and craftsmen in the Qin State ingeniously innovated the interpretation of pagodas as Grottoes in Cave 4 of Maijishan, leaving behind a valuable Buddhist and artistic legacy for future generations. The author will detail the architectural language of Cave 4 in the following text to further substantiate the hypothesis that the architectural form of the niches in Cave 4 imitates a single-story wooden pagoda.

7. The similarity between architectural elements in the interior of niches and the single-story wooden pagoda

The interior of the niches of Cave 4 has unique designs: octagonal columns, column bases with overturned lotus motifs, painted wooden joints, three layers of shallow relief on the walls, and the five overturned lotuses on the top. These architectural elements are not random decorations, but the necessary expression to construct an embedded pagoda in the cave.

7.1. Octagonal columns

The stone-core clay sculpture, imitating wooden octagonal columns, is one of the typical characteristics of Cave 4, which some researchers have taken to be the supporting evidence of the theory of the imitated Dou Zhang.

However, Dai pointed out in his paper that the diameter of the rods of Dou Zhang excavation is usually only 2–3 cm, while the dimension of octagonal columns in Cave 4 is much greater. This implies the distant relationship between the two designs. Moreover, the octagonal columns and their bases in the interior of niches (**Figure 3**) are consistent with the octagonal columns in the outside Buddha hall with a hip roof, which means the columns in the interior of niches are more likely to be imitation of wooden architectures that match the hip roof hall well rather than Dou Zhang [4,22].

Sicheng Liang believes that the octagonal shape and the gradual shrinking dimension from the bottom to the top of the columns in grottoes created in the Northern Wei and Northern Qi Dynasties accurately imitate the shape of contemporary wooden columns [10].

Both the Northern Zhou and Northern Qi Dynasties preserved the style and core techniques of architecture of the Northern Wei Dynasty. After the relocation of the capital of Northern Wei, Buddhists in Maijishan were also affected by Pingcheng, Luoyang, and Changan where Buddhism thrived the most. Stone octagonal columns in the Great Buddha Cave at Xiangtangshan Grottoes, which imitate wooden octagonal columns, were created at the same time as Cave 4's creation and have various similarities with octagonal columns in Cave 4. The octagonal columns in the Great Buddha Cave at Xiangtangshan Grottoes offered reference to stone-core clay sculpture imitating wooden octagonal columns in Cave 4; this implies that the octagonal columns in niches aim to imitate the octagonal columns in wooden Buddhist architecture. The preserved great octagonal columns in the central Buddha hall of Jokhang Temple created in the Tang Dynasty show how common it was that the octagonal columns were used in Buddhist architecture.

The stone-core clay sculpture imitating wooden octagonal columns of niches in Cave 4 is more symbolic while the octagonal columns in the Great Buddha Cave have a more realistic style. Considering the size, these columns are more reasonably an imitation of the wooden architecture rather than the removable Dou Zhang.

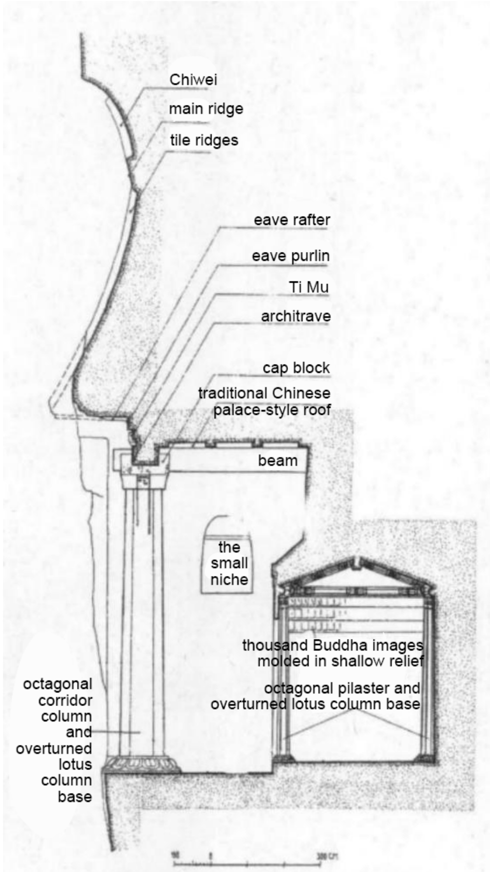
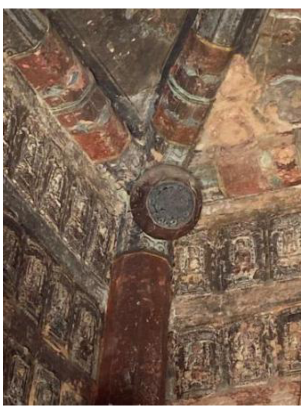


Figure 3. The long section of Cave 4 (Source: Dunhuang Research, 2013(2): 22)

Table 3. Octagonal columns in grottoes from the late Northern Dynasty

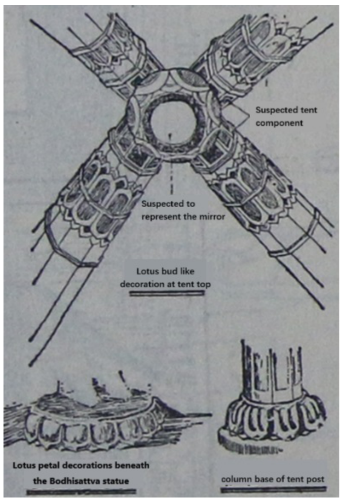
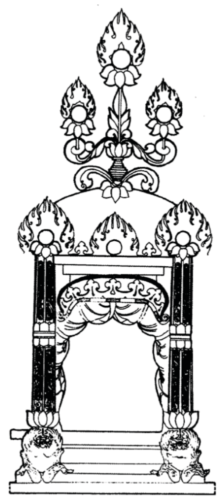
Name of the Cave	Cave 4, Maijishan Grottoes, by the author	Cave 8, Yungang Grottoes, by Sicheng Liang [10]	Shaka Cave, Xiangtangshan Grottoes [11]
Imitated wooden octagonal columns			

Considering both the columns of the hip roof and in the niches, and the purpose of the overall architectural style, the author believes that the octagonal columns in the niches of Cave 4 are imitations of columns of wooden Buddhist architecture in the Northern Zhou Dynasty rather than rods of Dou Zhang.

7.2. Lotus-shaped bands

The octagonal pillars within the niche of Cave 4 at Maijishan Grottoes are adorned with lotus-shaped band decorations, which, despite weathering, remain distinctly visible and recognizable in their patterns and forms. Such lotus-shaped bands are not only found in Cave 4 but are also commonly seen in the construction of other pagodas and Buddhist temples. For instance, similar lotus-shaped bands are carved on the pillars of the Great Buddha Cave Pagoda at Xiangtangshan, as well as in Caves 1 and 2 of Southern Xiangtangshan, and Caves 2 and 3 on the Eastern Peak of Tianlongshan.

Table 4. Lotus-shaped bands in late Northern Dynasty

Name of the cave	Cave 4, Maijishan Grottoes [9]	Great Buddha Cave, Xiangtangshan Grottoes [12]
Lotus-shaped Band		

It is also recorded in the architectural history of the Northern Dynasty that the wooden joints are very similar to lotus-shaped bands in Cave 4 (**Figure 4**) [7].

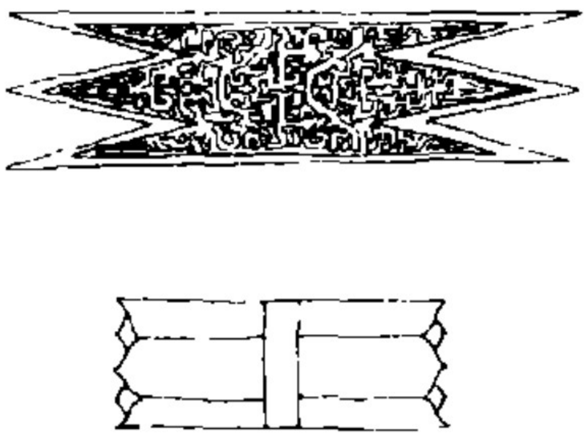


Figure 4. The golden normal bands and lotus-shaped bands

Although it cannot be completely concluded that the lotus-shaped bands are an imitation of wooden joints based on their application, the similarity between them still supports the hypothesis that the niches of Cave 4 imitate wooden Buddhist architecture.

7.3. Stone column bases in an overturned lotus pattern

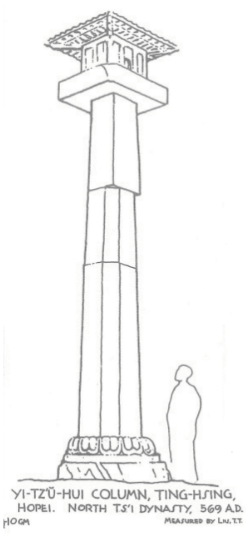
The stone lotus column base beneath the octagonal pillar within the niche of Cave 4 at Maijishan is equally noteworthy. To prevent the bottom of wooden pillars from moisture damage and decay, high-grade ancient Chinese architecture often employed stone column bases beneath wooden pillars for long-term preservation, a practice also observed in Buddhist architecture.

Portable and lightweight, the Dou Zhang does not necessitate the presence of stone column bases. The stone column base in Cave 4, however, is more likely to be a load-bearing and moisture-proof accessory characteristic of traditional Chinese wooden architecture. Stone lotus bases from the Northern Dynasties still exist, such as the Yici Hui stone pillar base in Dingxing, Hebei, which features a top in the form of a Buddhist temple, an octagonal pillar body, and a stone lotus column base carved at the bottom. Cave 1 on the eastern peak of Tianlongshan, which was excavated during the Northern Qi period, also has stone lotus column bases carved beneath its octagonal pillars outside the niches.

The lotus is an important motif in Buddhism. The tradition originated from both India and Greece, as recorded, "The lotus is a sacred motif of Buddhism. Though it originated from India, the design of its petals is evidently from the egg-and-dart pattern in Greece" [10].

The lotus-adorned column base beneath the octagonal columns within the niche of Cave 4 at Maijishan Grottoes exhibits a striking similarity to the octagonal stone columns from the Northern Qi Dynasty, specifically the Dingxing Yici Hui's octagonal stone column, as well as the lotus-covered column bases, carved on the Buddha Hall pillars of the Great Wild Goose Pagoda from the Tang Dynasty. This consistency suggests a continuous architectural tradition of employing lotus motifs as column bases in Buddhist structures from the late Northern Dynasties through to the Tang Dynasty. The presence of the stone lotus column base within the niche of Cave 4 further substantiates the argument that the niche is designed in the style of Buddhist architecture rather than Dou Zhang.

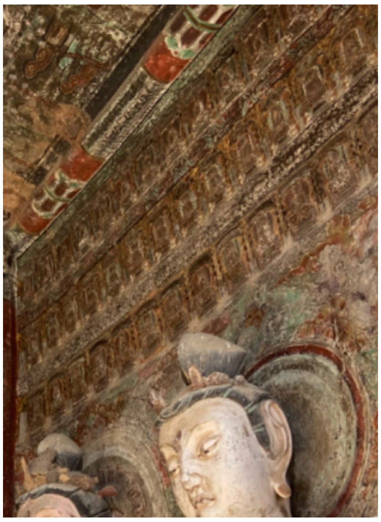
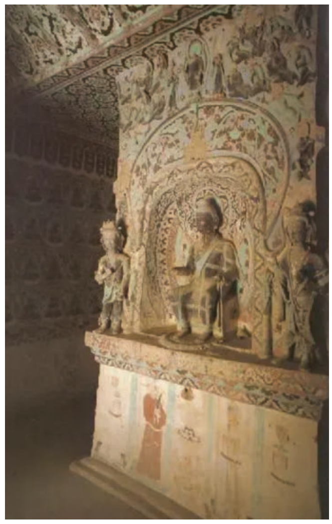
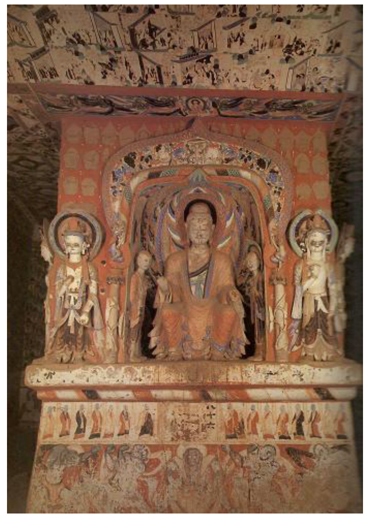
Table 5. Late Northern Dynasties Buddhist architecture: lotus-base pillar foundations

Name of the Cave	Yici Hui Stone Pillar, Northern Qi Dynasty, by Sicheng Liang [10]	Cave 1, Tianlongshan Grottoes, Northern Qi Dynasty [13]
Pattern of the column base		

7.4. Three-story shallow relief on the upper section of walls in the interior of niches

The three-story of shallow relief in the niches are also worth noticing. Shallow relief has long been used as a decoration on pagodas. Early pagodas in India are decorated with narrative paintings of Sakyamuni's previous lives. The excavation of the Yongning Temple from the Northern Wei Dynasty led to the finding of more than three hundred small statues, most of them shallow reliefs originally attached to the walls [14]. The shallow relief has already been a feasible decoration on pagodas during the Northern Wei Dynasty.

Table 6. Shallow relief in grottoes from the Northern Dynasty

Name of the cave	Cave 4, Maijishan Grottoes, Northern Zhou Dynasty shallow relief in the interior of niches	Cave 437, Mogao Grottoes, Northern Wei Dynasty Shallow relief on the niche on the front of the center pillar [15]	Cave 290, Mogao Grottoes, Northern Zhou Dynasty shallow relief on the front of the center pillar [15]
Shallow relief			

The three-story shallow relief is similar to the shallow relief decorated on the central pillars in Cave 437 created in the Northern Wei and Cave 290, created in Northern Zhou in the Mogao Grottoes. The only difference is the shallow relief is placed on the interior of the niches in Cave 4, while it appears on the exterior of central pillars in the caves in the Mogao Grottoes.

Both Dunhuang and Qin State were affected by Buddhism in Luoyang, Changan and Northern Liang Dynasty, so the style of decorations of Grottoes in the two places have some similarities. It is then reasonable to conclude that the three-story shallow relief might also be an imitation of the pagoda in Cave 4.

7.5. Overturned lotus on the top of the interior of niches

The unique way the five overturned lotus are presented at the top of the interior of niches in Cave 4 is also worth noticing. The major Buddha statue is usually integrated with the body of the pagoda and is placed on the front of the pagoda. This practice continued from the Eastern Han Dynasty to the early Northern Wei Dynasty. Another practice that continued throughout the Eastward transmission of the pagoda in China is the circumambulation of the pagoda.

The design of Yungang Grottoes created before the relocation of the capital of the Northern Wei Dynasty separated the major Buddha statue and the pagoda: the designer put the pagoda in the front hall, while the statue is in the back hall. To emphasize the connection between the major Buddha statue and the pagoda, designers from the middle of the Northern Wei Dynasty usually used the roof of mchod-rten above the head of the major Buddha statue, and massive carvings of pagodas and niches on walls, so that the audience would be reminded that the statue was still in the pagoda. In Yungang Grottoes, the top of the caisson of the pagodas in the Buddha hall outside is mostly decorated with lotus and flying apsaras [10].

In grottoes like the Binyang Middle Cave and Lotus Flower Cave at Longmen Grottoes, and the Cave of the Engraved Scriptures at Northern Xiangtangshan Grottoes, the center pillar disappears from the center of the plan, and the place is replaced by the giant lotus on the roof. Twenty years after the creation of Xiangtangshan Grottoes, Cave 4 at Maijishan Grottoes also adopted five overturned lotus on the roof for decoration of niches.

Figure 5. The finial of the pagoda in Songyue Temple (Songyue Pagoda: 443 [16])

Having a finial is a typical characteristic of a pagoda, and the bases of the finial are usually squares [12]. However, instead of direct or alone use of the finial or a center pillar, what appears in cases like the top of the Buddha Hall of Yungang Grottoes, the top of Binyang Middle Cave and Lotus Flower Cave at Longmen Grottoes, the top of the Cave of the Engraved Scriptures at Northern Xiangtangshan Grottoes, the finial of the pagoda at Songyue Temple (**Figure 5**) are motifs and carvings of overturned lotuses. The five overturned lotuses might have a connection with the cases, the purpose of which might be explained.

The author believes that the overturned lotus in the Yungang Grottoes, Longmen Grottoes, Xiangtangshan Grottoes, and Cave 4 at Maijishan Grottoes, though different in size, all imitate the overturned lotus on the finial of the pagoda, especially considering the close connection of innovative replacement of central pillar in the Yungang and Longmen Grottoes. The top of a cave in grottoes represents the pagoda finial, while the pagoda finial implies the existence of the top of a pagoda. Considering the hardship the craftsmen might face if carving a complicated structure of finial, it is also reasonable for the designer to consider the overturned lotus as a typical symbol of the pagoda.

The implication of the overturned lotus on the top of the pagoda might be a new practice of the Buddhist architects in the Qin State after the central pillar was replaced by the overturned lotus in Binyang Middle Cave, Longmen Grottoes, in which they used the overturned lotus as a symbol of the pagoda. The five overturned lotuses are not only decorations but also the symbol of the pagoda and its finial, expressing the pagoda as grottoes to the audience.

Table 7. Overturned lotus on the roof of caves from late Southern and Northern Dynasties

Name of the cave	**Binyang Middle Cave, Longmen Grottoes, Northern Wei Dynasty [17]**	**Lotus Flower Cave, Longmen Grottoes, Northern Wei Dynasty[18]**
Pattern of the roof		
Name of the cave	**The Cave of the Engraved Scriptures, Northern Xiangtangshan Grottoes, Northern Qi Dynasty [19]**	**Cave 4, Maijishan Grottoes, Northern Zhou Dynasty**
Pattern of the roof		

8. The similarities between architectural elements on the exterior of niches and the single-story wooden pagoda

Past researchers barely focus on the characteristics of the top of the exterior of the niches in Cave 4. This section discusses the characteristics of elements, including the shallow relief on the top of the exterior of the niches, the small platform at the top, and the five banana leaf motifs for each of the niches. It will also analyze the close relationship between the elements and the design of single-story wooden pagoda.

8.1. Shallow relief on the exterior of niches

The preserved pavilion-style pagodas, created from the Eastern Han Dynasty to Northern Zhou Dynasty are mainly with a pyramidal roof. From the pictures taken by the drone, we can observe the similarity between the niches of Cave 4 and the top of the single-story pagoda with a pyramidal roof. It is worth noticing that the techniques used to create the shallow relief of the top of the exterior of the niches are similar to the techniques used in shallow relief of mchod-rten in the Great Buddha Cave at Xiangtangshan Grottoes (**Figure 6**), especially considering that the time the two caves were created is quite close. The shape and techniques used in shallow relief of the top of the niches in Cave 4 provide important clues for the origin of its architectural form [20].

The pyramidal roof, depicted on the exterior of the niches in Cave 4 is the major form, applied among existing pavilion-style pagodas, created during and before the Northern Zhou Dynasty. The shallow relief on the exterior is possibly a depiction of the pyramidal roof of the pavilion-style pagodas.

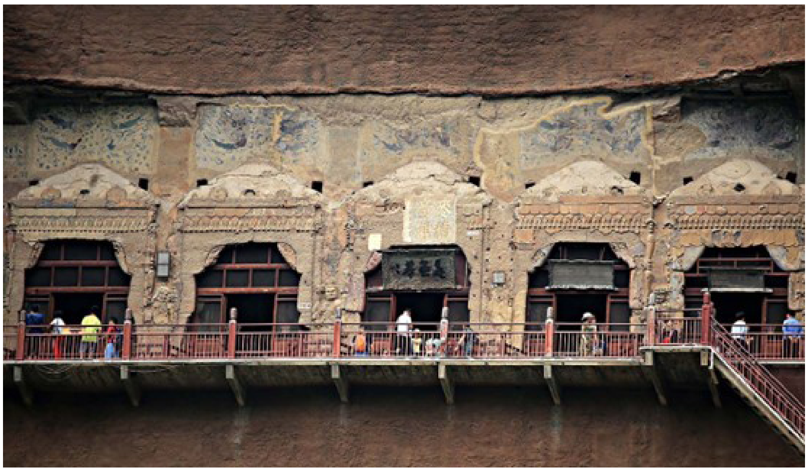


Figure 6. The plan view of Cave 4

8.2. Small platforms on the top of the exterior of niches

Although the top of the exterior of the niches looks like the top of Dou Zhang; the latter does not have the small platform at the top, nor does the canopy tent. Considering the great difference between the exterior of Cave 4 and Dou Zhang, it is unlikely that the former imitates the latter. It is more likely that the small platforms imply the existence of a finial base of pagodas. Past researchers have ignored the design of the small platforms, including the sketching of the exterior of Cave 4 and Cave 5 at Maijishan Grottoes created by Xinian Fu [9].

A similar design also appears in the carvings of the finial of the pagoda in Cave 2 at Yungang Grottoes (**Figure 7**) in which the finial base of the pagoda is represented by the relief of a platform [21].

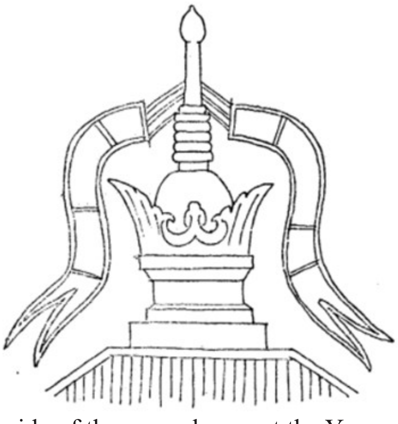
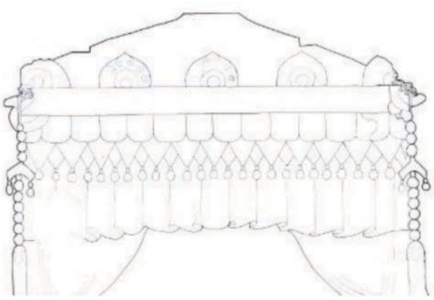
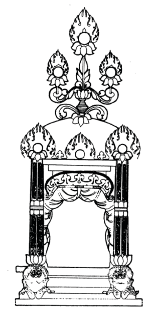
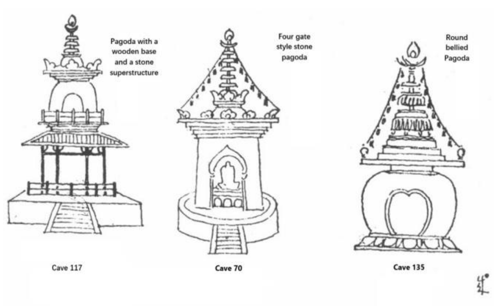
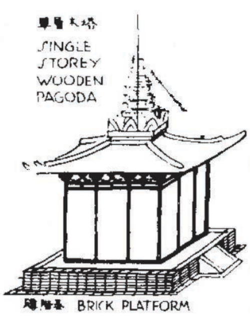


Figure 7. The relief stupa finial on the east side of the second cave at the Yungang Grottoes (Source: The Origin of Ancient Chinese Pagoda Spires: 56)

8.3. Five banana leaf motifs on the top of the exterior

The banana leaf motif on the exterior of the niches in Cave 4 is quite similar to the decoration on the top of the single-story, mchod-rten in Great Buddha Cave at Xiangtangshan Grottoes. Similar decorations are also found in Cave 70 at Yungang Grottoes and single-story pagodas in the murals from the Tang Dynasty in Mogao Grottoes. As a typical decoration on the top of a pagoda, the existence of the banana leaf motifs on the exterior of niches also supports the imitation of Cave 4's niches to the single-story pagodas.

Table 8. Comparison of the banana leaf motif in Cave 4 and the decoration of the roof of existing pagodas

Location	Banana Leaf Motif on the top of exterior of niches in Cave 4, Maijishan Grottoes, illustrated by Ming Zhang [8]	Decoration on the top of the Great Buddha Cave, Xiangtangshan Grottoes, Northern Qi Dynasty [12]
		
Single Layer Pagoda	Decoration on the top of single layer pagoda in Cave 70, Yungang Grottoes, Northern Wei Dynasty [22]	Banana Leaf Motif on single-layer wooden pagoda in a mural from Dunhuang, Tang Dynasty [10]
		

The shallow relief, depicting the pyramidal roof, the small platform similar to the finial base, and the banana motif, all imply that Cave 4 might imitate the form of single-story wooden pagodas.

9. Conclusion

This paper raises doubts about the theory of the imitation of Dou Zhang. Through a comparison of architectural elements in Cave 4 of the Maijishan Grottoes and wooden pavilion-style pagodas from before the late Northern Dynasty, it examines their similarities. From the perspective of Buddhist culture, the religious significance of pagodas aligns more appropriately with elements such as the hip roof.

The architectural form of Cave 4 is more likely the imitation of a single-story pavilion-style wooden pagoda with a pyramidal roof decorated with drapery, rather than Dou Zhang or nomadic tents. This paper has provided evidence, including the consistency of architectural styles among elements, the progressing design in religious space, the similarity among elements like octagonal columns and their bases, lotus-shaped bands, the three layers of shallow relief, the five overturned lotus on roof symbolizing the top of the pagoda, the joints imitating wooden architecture on columns, the shallow relief depicting finial of pagoda on the exterior of the top of niches, the banana leaf motifs on exterior of niches, and the popularity of single story pagodas from the Eastern Han Dynasty to the Northern Zhou Dynasty. The designs of Cave 4 might have embedded the pagoda in the cave and realized the innovative expression of a similarity between pagodas and grottoes in Buddhist architecture.

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Research on the Construction Mode and Value of Intelligent Construction Cultural Tourism Projects

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Abstract: In the process of cultural and tourism project construction, intelligent construction technology has gradually shown strong advantages. The effective application of this technology not only greatly improves the construction efficiency and quality of cultural and tourism projects, but also effectively controls construction costs, laying a solid foundation for the green, low-carbon, and sustainable development of the cultural and tourism industry. The article analyzes the current situation of cultural and tourism project construction, proposes the advantages of intelligent construction and its application in the construction mode of cultural and tourism projects, aiming to provide reliable guidance for the sustainable development of cultural and tourism projects.

Keywords: Intelligent construction; Cultural and tourism projects; Construction mode

Online publication: March 7, 2025

1. Introduction

Against the backdrop of rapid technological development, intelligent construction technology, with its efficient, precise, and sustainable characteristics, is gradually leading a profound transformation in the construction industry. In the field of cultural and tourism project construction, the application of intelligent construction has become a key driving force for improving project quality, accelerating construction processes, and reducing operating costs. With the integration of advanced technologies such as big data, cloud computing, and the Internet of Things, intelligent construction technology provides unprecedented design flexibility, construction accuracy, and intelligent operation and maintenance for cultural and tourism projects. Therefore, an in-depth exploration of the construction mode of cultural and tourism projects oriented towards intelligent construction and the value it brings has profound significance for promoting the transformation and upgrading of the entire cultural and tourism industry and high-quality progress.

2. Current situation of cultural and tourism project construction

In the context of current socio-economic development, the construction of cultural and tourism projects is advancing at an unprecedented rate, reflecting a notable shift toward diversification and expansion. From historical and cultural cities to modern theme parks, from natural landscape development to cultural experience projects, the types of cultural and tourism projects are becoming increasingly diverse, which can better meet the growing spiritual and cultural needs of the public. With the continuous advancement of cultural and tourism project construction, the drawbacks exposed by traditional construction methods are becoming increasingly prominent. The high construction costs, inefficient construction processes, and difficult to guarantee building quality have become the main bottlenecks restricting the further development of cultural and tourism projects [1]. Traditional construction methods often rely on manual operation and empirical judgment, lacking scientific management and advanced technical support, resulting in frequent problems such as resource waste, project delays, and uneven quality. In order to solve these urgent problems, intelligent construction has emerged, bringing new dawn and infinite possibilities to the construction of cultural and tourism projects [2]. Intelligent construction achieves digitalization, automation, and intelligence of the construction process by introducing advanced information technology, automation technology, and intelligent equipment. It can effectively reduce construction costs, improve construction efficiency, ensure building quality, and inject new vitality and momentum into the sustainable development of cultural and tourism projects.

3. Value of intelligent construction in cultural and tourism project construction

3.1. Reduce construction costs

The application of intelligent construction technology has played a crucial role in reducing the construction cost of cultural and tourism projects. Through precise construction simulation, intelligent construction can comprehensively and meticulously plan the construction process before the project starts, effectively reducing material waste during the construction process. At the same time, advanced design software enables intelligent construction to continuously optimize design plans, ensuring minimal material usage while still meeting project requirements [3]. Additionally, intelligent construction can significantly enhance efficiency through automated and smart construction methods, reducing labor costs, shortening the construction timeline, and ultimately lowering overall project costs. For example, intelligent robots and automation equipment can replace manual labor for dangerous or repetitive tasks, not only improving work efficiency but also reducing personnel safety risks. The intelligent construction management system can monitor the construction progress and resource consumption in real time, ensuring that the project progresses smoothly according to plan and avoiding additional costs caused by delays.

3.2. Improve construction efficiency

Intelligent construction technology can achieve intelligent and automated control of the construction process by integrating advanced information technology and automation technology, thereby effectively improving the progress of construction. During the construction process, intelligent devices can automatically perform preset tasks such as precise material handling, component assembly, etc., without frequent manual intervention, greatly improving construction speed. At the same time, the intelligent construction system can also monitor the construction status in real time, adjust the construction plan promptly, and respond to various unexpected situations that may arise. In addition, intelligent construction can also reduce the impact of human factors on construction progress. In traditional construction methods, human factors often become one of the main reasons for project delays. Intelligent construction, through precise construction simulation and automated construction management, can minimize human errors and delays, ensuring that projects can proceed smoothly as planned and be completed on time.

3.3. Improve the quality of construction

The application of intelligent construction technology in cultural and tourism project construction can ensure that every aspect of the building meets relevant standards and requirements through strict construction monitoring and quality inspection methods, thereby guaranteeing the overall quality of the building from the source. During the construction process, the intelligent construction system can monitor the construction status in real time and dynamically evaluate the construction quality. Once a quality issue is discovered, the system will immediately issue a warning and guide the construction team to take corresponding measures for rectification, ensuring that the problem is resolved promptly. In addition, intelligent construction can accurately measure and analyze building materials and components. With the help of advanced sensors and detection technology, intelligent construction can obtain real-time performance indicators of materials and components, ensuring that they meet design requirements. This not only helps improve the durability of buildings but also significantly enhances their safety, providing tourists with a safer and more reliable cultural and tourism experience.

4. Analysis of the construction mode of cultural and tourism projects for intelligent construction

4.1. Application of BIM technology

BIM (Building Information Modeling) technology, as one of the core technologies in the field of intelligent construction, is gradually changing the traditional mode of cultural and tourism project construction. With its multiple advantages such as visualization, coordination, simulation, and optimization, BIM technology plays a crucial role in the design, construction, operation, and maintenance of cultural and tourism projects throughout their entire lifecycle. Firstly, in the design phase, BIM technology can assist designers in optimizing their design plans. By constructing precise 3D models, designers can more intuitively display the overall layout, spatial relationships, and detailed design of cultural tourism projects, making it easier to identify potential design issues and make corrections [4]. In addition, BIM technology also supports the adjustment and optimization of design parameters, which can make the design scheme more in line with aesthetic and economic requirements while meeting functional requirements.

Secondly, during the construction phase, the application of BIM technology is mainly reflected in the simulation and monitoring of the construction process. Through BIM technology, the construction team can simulate the construction plan in detail, including construction sequence, resource allocation, schedule control, etc., to ensure the smooth progress of the construction process. At the same time, BIM technology can also monitor construction progress and resource consumption in real time, identify and solve problems during the construction process in a timely manner, and effectively avoid project delays and cost overruns. Finally, in the operation and maintenance phase, BIM technology also plays an important role. Through BIM technology, the operation and maintenance team can easily access key information, such as building equipment and pipelines, enabling intelligent and efficient operation and maintenance management. This can not only improve operation and maintenance efficiency but also timely detect and handle equipment failures, ensuring the safe and stable operation of cultural and tourism projects.

Taking the Jinling Small Town Cultural and Tourism Project as an example, the project fully utilizes the advantages of BIM technology and carries out a series of work such as data gene coding, parameterized module construction, intelligent recognition, and precise mapping. Through BIM technology, the Jinling Small Town project has achieved digitalization and standardization of traditional wooden buildings, not only improving construction efficiency but also reducing construction costs. During the construction process, BIM technology also helps the construction team achieve visualization and refined management of the construction process, ensuring the quality and safety of the construction. During the operation and maintenance phase, BIM technology also provided strong support for the operation and maintenance management of the Jinling Small Town project, achieving intelligent and efficient operation and maintenance management.

4.2. Construction of lean construction system

Lean construction, a production management concept derived from the manufacturing industry, focuses on continuously reducing waste, optimizing processes, and enhancing efficiency. In the construction of cultural and tourism projects, the establishment of a lean construction system is not only an innovation of traditional construction methods but also an important guarantee for promoting high-quality and efficient completion of projects. Firstly, lean construction emphasizes the optimization and efficient utilization of resources. In the construction of cultural and tourism projects, it is necessary to plan materials, equipment, manpower, and other resources reasonably from the design stage to ensure that each resource can be maximally utilized. Through precise construction plans and strict cost control, lean construction can effectively reduce resource waste and lower project costs.

Secondly, lean construction emphasizes the refined management of the construction process. The construction team should have a high degree of collaborative work ability and be able to advance the work in an orderly and efficient manner according to the established construction plan. Under the lean construction system, every step of the construction process is carefully analyzed and optimized to ensure a smooth and efficient workflow. Meanwhile, lean construction also emphasizes strict control over construction quality. Through regular quality inspections and evaluations, it can ensure that project quality meets relevant standards and requirements. Thirdly, lean construction also focuses on improving the collaborative work ability of the construction team. In the construction of cultural and tourism projects, the construction team is often composed of multiple professional groups, each responsible for different construction tasks. Lean construction can promote information sharing, communication, and collaboration among teams by introducing advanced project management methods and tools such as project management software and collaborative work platforms. This not only improves work efficiency but also enhances the overall collaborative combat capability of the team, ensuring that projects can be completed on time and with quality.

4.3. Collaborative application of lean construction and BIM technology

The collaborative application of lean construction and BIM technology is an innovative and efficient model in the intelligent process of cultural and tourism project construction. The combination of these two technologies can not only leverage their respective advantages, but also complement and promote each other, bringing revolutionary changes to the construction of cultural and tourism projects. On the one hand, BIM technology provides precise data support and construction simulation for lean construction with its powerful visualization and simulation features. BIM technology enables project teams to create precise 3D building models, allowing for the visual representation and analysis of design concepts. This not only helps identify potential design issues but also facilitates detailed simulations prior to construction. By predicting various scenarios during the construction phase, BIM provides a data-driven foundation for informed decision-making, ensuring more accurate and efficient construction processes [5]. At the same time, BIM technology can also update project data in real time, ensuring the accuracy and timeliness of information in the lean construction process.

On the other hand, the concept and methods of lean construction can guide the application and optimization of BIM technology. Lean construction emphasizes reducing waste and improving efficiency, which requires the application of BIM technology to closely focus on project goals and carry out refined management and optimization. In the application process of BIM technology, the project team needs to follow the principles of lean construction, continuously optimize, and adjust the model to ensure a smooth and efficient construction process. At the same time, lean construction emphasizes teamwork and continuous improvement, which requires the application of BIM technology to have good information sharing and communication mechanisms, so that team members can timely understand project progress and problems and jointly promote the successful implementation of the project. In short, the collaborative application of lean construction and BIM technology is an important mode of intelligent construction in cultural and tourism project construction. The promotion and application of this model will help improve the construction level of cultural and tourism projects and promote the sustainable development and value to the cultural and tourism industry.

5. Conclusion

In summary, the application of intelligent construction in cultural and tourism project construction has significant advantages. Through BIM technology, lean construction system, and their collaborative application, it is possible to reduce construction costs, improve construction efficiency, and ensure building quality and maximize the project value. In the future, with the continuous development and improvement of intelligent construction technology, its application prospects in cultural and tourism project construction will be even broader. Therefore, in the construction process of cultural and tourism projects, it is necessary to actively promote and apply intelligent construction technology to promote the sustainable development and the value of the cultural and tourism industry.

Disclosure statement

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Hazard Analysis of Dam Corridor Cracks Based on Field Detection and Numerical Calculation

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Abstract: The longitudinal cracks distributed along the dam axis in the corridor of a dam may have potential safety hazards. According to the detection results of crack depth and width and the analysis of monitoring data, a three-dimensional finite element model is established for numerical simulation calculation and the influence of cracks on the safety of dam structure is analyzed from different aspects such as deformation, stress value, and distribution range. The calculation results show that the maximum principal tensile stress value and the location of the dam body are basically independent of the change of crack depth (within 1.0 m). Regarding local stress around the corridor, the high upstream water level causes cracks to deepen, resulting in an increase in the maximum tensile stress near the crack tip and an expansion of the tensile stress region.

Keywords: Gallery cracks; Field test; Finite element calculation; Hazard analysis

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1. Introduction

The concrete cracks of the dam affect the appearance, durability and safety performance of the dam structure, especially the unstable cracks, which bury hidden dangers to the stable operation of the dam [1]. It may not only cause economic losses, but also lead to dam accidents and endanger the safety of people's lives and property [2]. Therefore, the study of structural safety of slit dam is one of the important topics of dam construction and operation in various countries [3–11].

In this paper, the longitudinal cracks distributed along the dam axis in a dam corridor are taken as an example. The physical and mechanical parameters of the dam body and foundation materials are inversely calculated using dam monitoring data from the past 10 years. The derived parameters are then incorporated into the finite element analysis. Combined with the field crack survey, the depth and width data of the crack are detected. The dam model containing cracks data is established in finite element analysis and the harmfulness of the current cracks is analyzed. The analysis results indicate that under the influence of a high upstream water level, an increase in crack depth leads to higher maximum tensile stress near the crack tip and an expansion of the tensile stress region, posing a threat to dam safety. This paper also pre-analyzes the further expansion of cracks to a certain depth, which can provide reference for similar projects.

2. Project profile

A hydropower station project is composed of main dam, auxiliary dam, flood discharge building, dam powerhouse, vent pipe and switch station. The main dam of the river is a concrete open-web gravity dam. The maximum dam height is 95.5 m, and the total length of the dam top is 379.2 m. It is divided into 24 dam sections, of which 10^{th} – 16^{th} dam sections are concrete open-web gravity dam sections. In June 2007, during the daily inspection, it was found that there were longitudinal cracks distributed along the dam axis in the vault of the 7^{th} – 20^{th} dam section of the 85 m elevation corridor, the vault of the 55 m elevation corridor and the arch of the powerhouse.

3. Crack detection and preliminary analysis

In September 2015, 94 and 6 typical detection points were respectively arranged in the dam section with cracks in the 85 m elevation corridor and the 55 m corridor, and the depth and width of cracks were detected by ultrasonic wave. The results show that the maximum crack width of the 55 m elevation corridor is 0.74 mm and the maximum crack depth is 228 mm. The maximum seam width of the corridor at 85 m elevation is 1.00 mm and the maximum seam depth is 344 mm. The surface properties of the cracks are characterized by cracking or subtle regularity. Typical on-site inspection photos are shown in **Figure 1**.

Figure 1. Field detection photos of typical cracks.

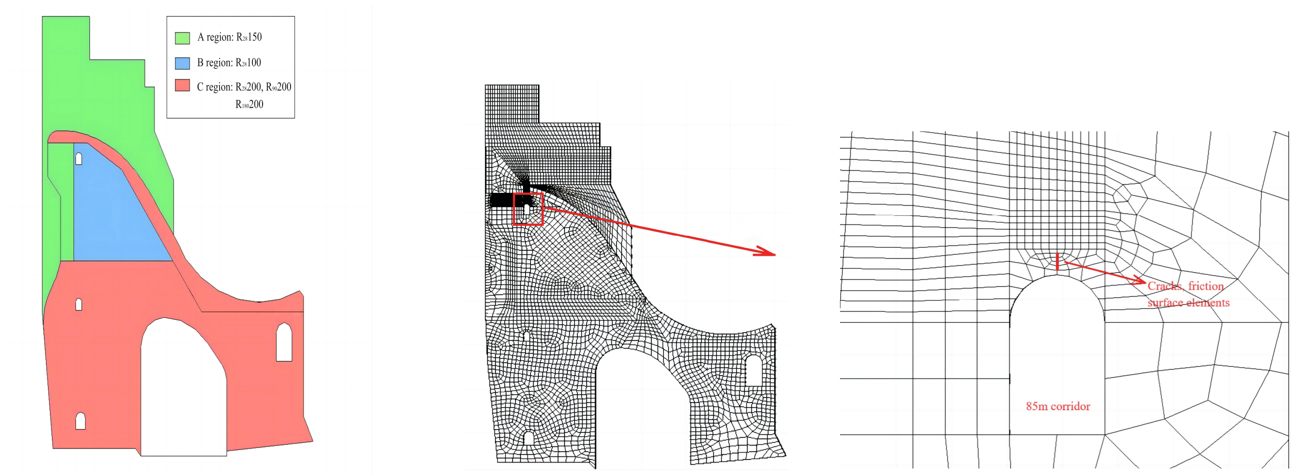
From the crack detection results, the crack depth and width of the 55 m elevation corridor are not large, and the cracks in the 85 m elevation corridor are relatively serious. Considering that the 85 m elevation corridor is close to the overflow surface, it may have a relatively large impact on the safety of the dam structure.

4. Hazard analysis of cracks

The 12th dam section of the installation room is selected to establish a three-dimensional model for calculation and analysis. Here, the hazard of cracks is evaluated from two aspects: one is to compare the difference of stress value and distribution around the corridor under the two conditions of with and without cracks; the second is to predict the change of stress value and distribution around the corridor by assuming that the crack further deepens to a certain depth. Based on the results of crack detection, the 12th typical dam section is selected as the research object to analyze the influence of cracks on the safety of dam structure.

4.1. Finite element model

The dam height of the 12th dam section is 90.5 m, and the width of dam bottom is 67.5 m. The range of finite element calculation model is that the dam foundation extends vertically downward more than twice the maximum dam height, and extends horizontally twice the dam height in the upstream and downstream directions. The finite element calculation model is shown in **Figure 2**. The bottom boundary of the foundation part of the model is a fixed constraint, the upstream and downstream sides of the foundation, the left and right sides of the foundation and the dam body are normal constraints, and the rest of the interface is free.



(a) **(b)** **(c)**

Figure 2. The finite element model and crack grid division of the 12th dam section: (a) Dam material subzone in finite element model; (b) Dam grid division in finite element model; (c) Local amplification in finite element model of 85 m corridor.

4.2. Load and calculation conditions

The calculated load mainly includes hydro-static pressure, dam body weight, dam foundation uplift pressure and silt pressure. The upstream water level is set under four conditions: normal storage level (105 m), design flood level (107.94 m), check flood level (112.04 m), and dead water level (80 m). For each water level condition, three crack scenarios—no crack, crack depth of 0.4 m, and crack depth of 1.0 m—are considered, resulting in a total of 12 calculation conditions.

4.3. The initial value of the material parameter

According to the working conditions and stress characteristics of different parts of the dam, the dam is divided into three areas as shown in **Figure 2 (a)**. Different materials and material parameters are selected for each area to achieve the purpose of optimizing design, saving materials, reducing costs, and improving engineering safety. Based on the 10 years of serial measured deformation monitoring data, an inversion analysis is made on the physical mechanical parameters of the dam body and foundation and the physical mechanical parameters of the dam body and the bedrock materials are obtained as shown in **Table 1**.

Table 1. Material calculation parameters of dam body, dam foundation and friction surface

Material	A region	B region	C region	Bed rock	Cracks (friction surface)
Volumetric weight γ(kN/m^3)	24	24	24	26.8	/
Elastic modulus E(GPa)	21.96	18.23	26.12	26.0	/
Poisson ratio μ	0.167	0.167	0.167	0.167	0.167
Prism compressive strength fc(MPa)	6.24	3.84	8.64	150	/
Axial tensile strength ft(MPa)	0.79	0.58	1.02	/	/

4.4. Calculation and analysis results of crack hazard

4.4.1. Deformation characters analysis

The calculation results show that in terms of the overall deformation of the dam, the presence or absence of cracks or the increase of crack depth (within 1.0 m of crack depth) does not affect the deformation value and distribution law. Under the action of three typical high water levels, which are normal water level (105.00 m), design flood level (107.94 m), and check flood level (112.04 m) in the upstream the cracks in the vault of the corridor become narrower than the initial crack width (1.0 mm). As the water level rises, the degree of crack closure increases. In the same water level and different crack depth conditions, the closure decreases with the increase of crack depth. The maximum closure of the seam width relative to the initial 1 mm is 0.11 mm. Under the influence of the upstream low water level (dead water level 80 m), the crack is primarily affected by the self-weight of the dam body, causing it to widen beyond the initial crack width. With the increase of crack depth, the opening amount increases, and the maximum opening of the crack width relative to the initial 1 mm is 0.04 mm.

4.4.2. Analysis of stress characteristics

The calculation results show that the maximum principal tensile stress value and the location of the dam body are basically independent of the change of crack depth (within 1.0 m). In terms of local stress around the corridor, under the action of high water level in upstream, the deepening of cracks leads to the increase of the maximum tensile stress near the crack tip and the expansion of the tensile stress area. When the fracture depth is 1.0m and the upstream water level is 105.00 m, 107.94 m, and 112.04 m respectively, the maximum tensile stress near the fracture tip is 0.23 MPa, 0.31 MPa, and 0.36MPa respectively. Under the influence of the upstream low water level (80 m), the maximum tensile stress around the corridor at the same fracture depth is higher than that under high water level conditions and increases as the crack deepens. When the fracture depth reaches 1.0 m, the maximum principal tensile stress reaches 0.37 MPa. The local stress around the corridor under various working conditions is shown in **Table 2** and the stress distribution of the dam under typical working conditions is shown in **Figure 3**.

Table 2. Summary of stress characteristic values under different working conditions

Working condition	Water level	Penetration concept of fracture	Maximum tensile stress (MPa)	Extreme stress position	Distribution characteristics of tensile stress zone
1	105 m (Normal water level)	crack-free	0.03	Upstream side wall	The middle of the upstream side wall extends about 0.5 m upstream. The center of the bottom plate extends downward about 0.2 m.
2		0.4 m seam depth	0.15	Seam tip	The middle of the upstream side wall extends about 0.5 m upstream. The upstream and downstream sides of the fracture extend about 0.4 m, and the extension to the interior does not exceed the depth of the fracture.
3		1.0 m seam depth	0.23	Seam tip	The middle of the upstream side wall extends about 0.5 m upstream. The upstream and downstream sides of the fracture are expanded by about 0.8 m, and the internal extension does not exceed the depth of the fracture.
4	107.94 m (Design flood level)	crack-free	0.04	Upstream side wall	The middle of the upstream side wall extends upstream by about 0.6 m. The center of the bottom plate extends about 0.3 m.
5		0.4 m seam depth	0.20	Seam tip	The middle of the upstream side wall extends upstream by about 0.6 m. The upstream side of the fracture expands by about 0.7 m, and the downstream side expands by about 0.4 m. The extension to the interior does not exceed the depth of the fracture.
6		1.0 m seam depth	0.31	Seam tip	The upstream side wall is connected with the top arch crack and extends upward.
7	112.04 m (Check flood level)	crack-free	0.05	Upstream side wall	In the middle of the upstream side wall, it extends about 0.7 m upstream; the center of the bottom plate extends about 0.3 m.
8		0.4 m seam depth	0.22	Seam tip	In the middle of the upstream side wall, it extends about 0.7 m upstream; the upstream side of the fracture expands by about 0.8 m, and the downstream side expands by about 0.5 m, and the extension to the interior does not exceed the fracture depth.
9		1.0 m seam depth	0.36	Seam tip	The upstream side wall is connected with the top arch crack and extends upward.
10	**80 m (Dead water level)**	crack-free	0.25	Top arch	Area near the top arch and floor.
11		0.4 m seam depth	0.34	Seam tip	Area near the top arch and floor.
12		1.0 m seam depth	0.37	Seam tip	Area near the top arch and floor.

As shown in **Table 2**, the maximum tensile stress increases with the increase of crack depth under four different water levels. Compared with the upstream high water level state (105 m, 107.94 m and 112.04 m), the cracks will produce larger tensile stress.

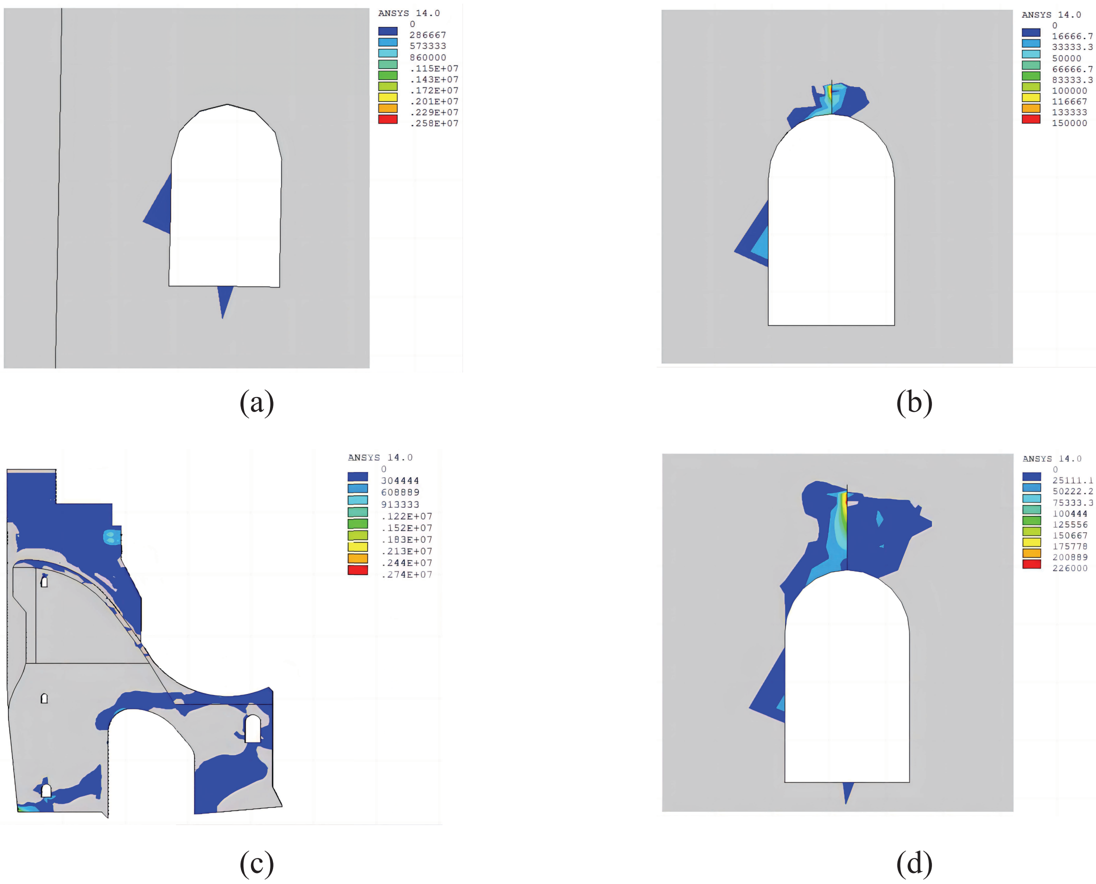


Figure 3. Stress distribution diagram of typical working conditions under normal water level(Unit: Pa): (a) Local stress distribution of corridor in working condition 1; (b) Local stress distribution of corridor in working condition 2; (c) Tensile stress distribution of dam body in working condition 3; (d) Local stress distribution of corridor in working condition 3.

As shown in **Figure 3**, under the normal water level (105 m), the tensile stress distribution around the corridor shows that the tensile stress is mainly distributed in the middle of the wall near the upstream side of the corridor. As the crack depth deepens, the tensile stress of the corridor vault increases, and the maximum tensile stress is generated near the crack tip.

5. Conclusion

The longitudinal cracks along the dam axis in the corridor of this project may pose potential safety hazards. The corridor at the 85 m elevation is near the overflow surface, which could have a significant impact on the structural safety of the dam. Based on the test results of crack depth and width, the 12th typical dam section was selected as the research object, and a three-dimensional finite element model was developed for numerical simulation analysis. The stress value and distribution around the corridor are compared under conditions with and without cracks. Additionally, assuming the crack deepens to a certain extent, the resulting changes in stress value and distribution around the corridor are analyzed.

After calculation and analysis, the maximum principal tensile stress of the dam around the corridor under

12 working conditions is lower than the allowable tensile strength of 100 concrete (0.58MPa). The influence of cracks on the stress around the corridor is still limited under the condition of checking flood level. It can be considered that the cracks in the corridor do not threaten the safety of the dam structure when the water level is high.

During the future operation of the dam, when the reservoir water level is low, the tensile stress on the gallery vault increases due to the influence of the dam's self-weight. Therefore, monitoring the crack opening should be strengthened. When the reservoir water level is high, monitoring the overall displacement of the dam, including the displacement of the dam top and the 85 m elevation corridor, should be strengthened. Additionally, attention should be given to changes in crack opening and closing, and any abnormalities should be promptly analyzed to determine their causes. If necessary, some reasonable measures should be taken such as chemical grouting, surface sealing treatment, and use of seam materials to reinforce the structure of corridor cracks.

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Research on Construction Operation and Maintenance Management Based on BIM Technology

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Abstract: With the rapid advancement of information technology, Building Information Modeling (BIM) is being increasingly utilized in the construction industry, demonstrating significant potential and value in construction operations and maintenance management. Based on this, this paper conducts an in-depth discussion on BIM technology in building operation and maintenance management, analyzing its challenges and countermeasures, with the aim of providing readers with useful insights and references.

Keywords: BIM technology; Building operation and maintenance management; Information integration

Online publication: March 7, 2025

1. Introduction

With the rapid advancement of urbanization in China, the construction industry has entered a phase of significant growth, making building operation and maintenance management a crucial aspect of ensuring the safe and efficient functioning of buildings. Traditional building operation and maintenance management mostly relies on drawings, manual inspection, and experience judgment, which leads to problems such as resource waste. Therefore, exploring a new, efficient, and intelligent building operation and maintenance management mode has become an important issue to be solved urgently in the current construction industry.

2. BIM technology foundation and overview of building operation and maintenance management

2.1. BIM technology core concept and technical framework

BIM technology is an innovative technological approach in the construction industry that integrates a building's physical and functional characteristics, representing and managing them in a digital format. BIM technology is developed around the BIM model, which serves not only as a shared knowledge resource for information related to engineering projects but also as the foundation for key business processes such as design, construction, and operation. Through BIM modeling, all project participants can use the same information at the same time to carry out multi-scheme comparison, sustainability analysis, efficient design, construction site control and other business activities, thus greatly improving the decision-making efficiency and quality of engineering projects [1].

In terms of technical architecture, BIM technology relies on key elements such as 3D modeling, data integration, collaboration platforms, multidisciplinary analysis, and project management. Among them, 3D modeling is the cornerstone of BIM technology, which enables designers and engineers to understand the project more intuitively by creating a digital model that includes all the details of the building. The data integration function can ensure the real-time sharing and updating of project information, avoiding the appearance of information islands, and further improve the overall work efficiency [2].

2.2. The definition and content of building operation and maintenance management

Construction operation and maintenance management refers to a series of operation and maintenance comprehensive management activities after the construction project is completed and put into use. This approach effectively integrates key resources such as personnel, facilities, and technology within the building, maximizing resource utilization, reducing operating costs, and enhancing investment returns through an efficient operation and feedback mechanism. The main contents cover space management, asset management, daily management, emergency management, energy consumption management, maintenance management, public safety management, and other aspects, which is the innovation of the traditional property management industry [3].

3. The application of BIM technology in building operation and maintenance management

3.1. Equipment maintenance and asset management

By enabling comprehensive equipment information management, BIM technology supports the entire lifecycle maintenance of construction equipment, including selection, installation, commissioning, operation, and maintenance. It accurately records essential data such as basic information, technical parameters, and maintenance history, establishing a solid foundation for efficient equipment management. During the equipment operation stage, the integration of BIM technology with monitoring systems enables real-time monitoring and data collection of equipment status. This allows for the timely detection of operational abnormalities and the prompt implementation of maintenance measures, effectively extending the equipment's service life. At the same time, BIM technology can automatically generate maintenance plans based on the equipment's operating status and maintenance requirements. By analyzing operational data and maintenance records, it can further optimize these plans, enhancing the reliability and availability of the equipment [4].

In terms of asset management, BIM technology can digitize the information of buildings, equipment, and other assets and use software platforms for management, maintenance, and analysis. BIM technology can realize the integration and visualization of asset information, so that managers can quickly check the location, attributes, status, maintenance history, and other information of assets, to quickly and accurately make decisions on the overall management of assets. Furthermore, BIM technology can also promote the efficiency of asset management and maintenance, including inventory maintenance, equipment tracking, maintenance management, inspection plan, etc., to make asset management more scientific and reasonable [5].

3.2. Work order management and process optimization

In terms of work order management, BIM technology can provide a detailed building information model, which integrates the design information of building structure, mechanical and electrical equipment, water supply and drainage system, and other aspects. Operation and maintenance managers can quickly locate the location of equipment based on the BIM model, understand its properties and running status, to generate and process work orders more efficiently. For example, when a certain equipment fails, the manager can find the equipment in the new BIM model, generate a maintenance work order by viewing its detailed information, and send it to the corresponding maintenance personnel. In addition, the visual characteristics of the BIM model also make the description of the work order more intuitive and accurate, effectively reducing the delay caused by information asymmetry [6].

The traditional operation and maintenance management process often has problems such as information island and poor communication, which leads to low efficiency of the overall process. BIM technology provides an integrated information platform so that the design, construction, operation, maintenance, and other stages of information can be seamlessly connected. In addition, BIM technology can also be combined with other advanced technologies such as the Internet of Things, cloud computing, etc., to further improve the efficiency and intelligence level of operation and maintenance management. For example, by transmitting the real-time operation data of equipment into the BIM model through the Internet of Things technology, managers can monitor the status of equipment in real-time and automatically generate work orders when necessary. Cloud computing technology provides powerful data processing and storage capabilities, enabling BIM models to be efficiently managed and shared in the cloud [7].

3.3. Energy management and environmental monitoring

BIM models are able to integrate data from smart building systems, including HVAC, lighting, occupancy sensors, etc. By monitoring and analyzing these data in real-time, smart building systems can identify potential energy-saving opportunities, automate control, and optimize algorithms to further reduce energy waste and improve overall efficiency. In addition, BIM technology also supports energy simulation, allowing architects and engineers to simulate and analyze different energy scenarios prior to implementation to determine the most effective strategies to reduce energy consumption and improve building performance. This data-driven approach to decision-making enables significant reductions in energy costs [8].

With the 3D modeling and visualization capabilities of BIM technology, environmental parameters such as air quality, temperature, humidity, etc. can be monitored in real-time and once these parameters exceed the safety threshold, the system will issue an alarm, helping to timely detect environmental problems, and take appropriate remediation measures. This is essential for maintaining the indoor comfort of the building and the health of its occupants. At the same time, BIM technology can also be used in water resources management to optimize the utilization efficiency of water resources and reduce waste by simulating the supply and demand of water resources as well as the recycling of water. In addition, BIM technology also plays an important role in waste management. By combining the waste management system with the building model, it can monitor the amount of waste generated in real-time, provide a scientific basis for the reasonable disposal of waste, and promote the green operation of buildings [9].

4. Challenges and countermeasures of BIM technology in building operation and maintenance management

4.1. Challenges faced by BIM technology in building operation and maintenance management

First of all, the lack of BIM models in existing buildings and the difficulty in data collection is a significant problem. Due to historical reasons or technical limitations, many existing buildings have not established BIM models. Even if these buildings are established later, the models may not accurately reflect the actual conditions of the buildings due to the difficulties in collecting and updating data information. As a result, the application of BIM technology in operation and maintenance management is greatly limited and it is difficult to give full play to its advantages.

Secondly, the integration and compatibility of BIM operation and maintenance management system is the key factor restricting its wide application. At present, there are many kinds of BIM operation and maintenance management systems on the market but the data formats and interface standards between the systems are not uniform, resulting in poor integration of the system, and it is difficult to achieve seamless docking with other systems. This not only increases the complexity and cost of operation and maintenance management but also may lead to the problem of information silos and information inconsistency. In addition, due to the difficulty in sharing and exchanging data between different systems, operations managers face challenges in acquiring and analyzing data, making it difficult to make timely and accurate decisions [10].

Moreover, the automation and intelligence level of BIM technology in operation and maintenance management needs to be improved. Although BIM technology has powerful data analysis and visualization capabilities, these capabilities have not been fully utilized in practical applications. Many operation and maintenance management systems still rely on manual operation and judgment, with a low level of automation and intelligence. This not only increases the cost and time cost of operations and maintenance management but may also reduce the accuracy and efficiency of operation and maintenance management. To improve the automation and intelligence level of BIM technology in operation and maintenance management, it is necessary to introduce advanced algorithms and technical means, such as machine learning and artificial intelligence, to realize intelligent analysis, processing of operation, and maintenance management data [11, 12].

Finally, the market environment is also an important factor restricting the application of BIM technology in operation and maintenance management. At present, the application of BIM technology in the field of operation and maintenance management is still in its initial stage and the market recognition is not high. Many owners and operation and maintenance managers have insufficient understanding of the value of BIM technology and lack of motivation to adopt BIM technology. To promote the application of BIM technology in operation and maintenance management, it is necessary to strengthen market publicity and promotion and improve the visibility and influence of BIM technology. At the same time, it is also necessary to formulate relevant policies and standards to guide and support the application and development of BIM technology in operation and maintenance management [13].

4.2. The application path of BIM technology in building operation and maintenance management

The application of BIM technology in building operation and maintenance management is a complex and detailed process, encompassing multiple stages—from BIM model creation and information integration to the formulation and implementation of operation and maintenance strategies.

First of all, the application of BIM technology in building operation and maintenance management starts from the creation of BIM model. This step usually starts at the design stage, requiring the design team to create highly refined 3D building models using BIM software (such as Revit). This model not only contains the geometric information of the building, such as structure, spatial layout, etc., but also integrates non-geometric information such as the model number and performance parameters of the equipment. This information provides a solid foundation for subsequent operation and maintenance management. In the design stage, the BIM model needs to be named according to the unified standard naming rules, so that it can be efficiently retrieved and used in the operation and maintenance stage. In addition, to ensure the accuracy and integrity of the BIM model, the design team needs to communicate closely with the operation and maintenance team to ensure that all key information is accurately entered [14].

As the building enters the construction phase, the information of the BIM model will be further enriched and improved. Construction teams can use BIM models to conduct construction simulations, predict potential construction conflicts, and optimize construction processes. At the same time, they can also feedback changes in the construction process to the BIM model in a timely manner to ensure that the model is consistent with the actual situation. The BIM model at this stage not only provides strong support for the construction management but also lays a solid foundation for the subsequent operation and maintenance management.

When the building is put into use, the BIM model becomes the core tool of operation and maintenance management. The operation and maintenance team can intuitively manage and monitor the building space, equipment, and facilities by using the BIM model. Through the BIM model, operation and maintenance personnel can clearly see the structure layout of the building, the distribution of equipment, and the connection relationship between various systems. This not only helps operation and maintenance personnel to quickly locate problem areas, but also improves the efficiency of repair and maintenance. In addition, BIM models can also realize real-time update and tracking of equipment information, providing strong support for preventive maintenance and troubleshooting of equipment.

In the process of operation and maintenance management, BIM technology can also be integrated with other intelligent systems (such as the Internet of Things, big data analysis, etc.) to further improve the intelligent level of operation and maintenance management. For example, by connecting BIM models to Internet of Things devices, operation and maintenance personnel can monitor the operating status of devices in real-time and discover and deal with potential faults in a timely manner. At the same time, using big data analysis technology, operation and maintenance personnel can also conduct in-depth analysis of energy consumption, equipment use efficiency, and other data of buildings, providing a basis for formulating more scientific and reasonable operation and maintenance strategies [15].

In addition to the above applications, BIM technology can also play more roles in building operation and maintenance management. For example, in disaster evacuation, BIM models can simulate the evacuation path and escape time of buildings, providing scientific basis for the formulation of emergency plans. In the aspect of building environment management, BIM technology can help operation and maintenance personnel visually observe the overall situation of the building, and reduce the cost and construction difficulty for future maintenance. In addition, BIM technology can also be used in building energy efficiency management, asset management, and other aspects to comprehensively improve the level of building operation and maintenance management.

5. Conclusion

In summary, with the rapid advancement of information technology, the application of BIM technology in the construction industry is continuously expanding, demonstrating significant potential and value in building operation and maintenance management. Through BIM model, operation and maintenance management personnel can intuitively and accurately grasp the information of the building, to make more scientific and reasonable decisions. At the same time, the integration of BIM technology with other intelligent systems has further enhanced the intelligence of operation and maintenance management, ensuring the safe and efficient operation of buildings. It has gradually become an indispensable tool in building operation and maintenance, providing strong support for safe, efficient, and sustainable building management. Therefore, the relevant staff should actively embrace this change, strengthen the research and application of BIM technology, and jointly promote the digital transformation and sustainable development of the construction industry.

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Study on the Evaluation Methodology of Landslide Susceptibility Based on Spatial-scale Analysis

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Abstract: Landslides are significant natural geological hazards. Landslide susceptibility evaluation involves the quantitative assessment and prediction of potential landslide locations and their probabilities. Research has explored susceptibility assessment methods based on spatial-scale analysis. This evaluation integrates two models—global and local scale—using a CNN model and a PSO-CNN coupled model. Key aspects include selecting evaluation factors and optimizing model parameters for landslide susceptibility at different scales. A major focus of current landslide research is utilizing prediction results to enhance prevention and control measures.

Keywords: Landslide susceptibility evaluation; Spatial-scale analysis; Lixian county; Geographical weighted regression; Particle swarm algorithm

Online publication: March 7, 2025

1. Introduction

Seismic landslides are phenomena in which seismic shaking causes a rock or soil mass to shear and slide a certain distance along a gently sloping surface [1]. Seismic landslides are the most common type of seismic geological hazards in large seismic events in mountainous areas within continents and are not only numerous and large in scale, but also extremely hazardous, often causing particularly serious damage to human activities [2]. Landslide risk assessment involves the quantitative evaluation and prediction of potential landslide locations, probabilities, and associated risks. The prediction results serve as a reliable foundation for landslide prevention and mitigation in mountainous regions, making it a longstanding focus of landslide research [3].

Landslide susceptibility evaluation methods are mainly divided into two categories, one is the simulation test method that uses geotechnical models combined with basic spatial geological information to predict the probability of landslides occurring in a specific area; the other is a statistical method to evaluate and predict the possibility of landslide occurrence in the study area by studying the relationship between landslide sample points and their geological environment through computer and mathematical statistics [4].

This paper explores a landslide susceptibility evaluation method based on spatial scale analysis. Drawing on theories and techniques from computer science, surveying and mapping, geology, and statistical analysis, a spatial scale model-based evaluation method is established. The study integrates two evaluation models—the CNN model and the PSO-CNN coupled model—and applies them to real-world cases for landslide susceptibility assessment. Additionally, the relationships among landslide susceptibility evaluation results, evaluation factors, and model parameters at different spatial scales are quantitatively analyzed. Evaluate model parameters at a spatial scale and quantitatively analyze their intrinsic relationships.

2. Research methodology

As a geological issue, landslide disasters exhibit spatial scale relevance. As natural phenomena occurring within specific temporal and spatial contexts, landslides inherently possess scale attributes. Additionally, as regional natural events, their main controlling factors, characterization features, and evolutionary processes are significantly influenced by scale [5]. Therefore, scale is an unavoidable issue in landslide susceptibility assessment. Addressing the limitations in theoretical methods and scale considerations in landslide susceptibility assessment, this study integrates theories and technical approaches from disciplines such as computer science, surveying and mapping, geology, and statistical analysis. Focusing on Li County in Sichuan Province as the study area and incorporating real-world cases, a methodological study on landslide susceptibility assessment is conducted based on multiscale analysis. A geographically weighted regression method is used for local segmentation and a coupled PSO-CNN model is established to complete the regional landslide susceptibility mapping. By comparing the results of different scales and different models, we explore the relationship between spatial scales and the results of landslide susceptibility evaluation, evaluation factors and parameters of the evaluation model, as well as the intrinsic reasons.

2.1. Establishment of a unified framework and process for multi-source data processing

In the challenging and important research field of landslide susceptibility evaluation, Geographic Information System (GIS) plays an important role as an indispensable hero behind the scenes. Among them, providing a unified data processing platform is an extremely key function. In the field of actual geographical research, the sources of spatial data are extremely complex, including the macro surface information captured by satellite remote sensing and the micro terrain dynamic data monitored by ground sensors [6]. GIS is like an efficient data integration master, which can methodically integrate these spatial data with different characteristics into standard projections and coordinate systems one by one. In this way, the original chaotic data has a unified spatial benchmark, which lays a solid foundation for the subsequent in-depth spatial analysis work, so that the analysis results are more scientific and accurate.

Moreover, with the aid of digital scanning, image recognition, and other advanced digital technologies, traditional paper maps containing rich geological information—such as topographic maps that accurately depict terrain relief, geological maps that reveal subsurface structures, and water system maps that illustrate water flow patterns—can be seamlessly integrated into the GIS platform. On this platform, the data contained in these paper maps are no longer isolated but are interrelated and complementary with other types of data, achieving a deep integration of data.

However, the multi-source data obtained by the above conventional methods are difficult to work together directly in landslide susceptibility assessment because of the differences in collection technology, storage specifications, and other relevant standards, just like individuals from different countries and speaking different languages. At this time, it is urgent to build a scientific and reasonable standard data processing framework. This framework is like an excellent translator, which can effectively eliminate the differences in data format, coordinate system, spatiotemporal resolution, projection, and other aspects so that all data can be accurately applied to landslide susceptibility evaluation in a uniform standardized format and provide strong data support for the prevention and management of geological disasters.

2.2. Scaling methodology in landslide susceptibility assessment identified

To quantify the effect of different scales on the results of landslide susceptibility evaluation, the best scale for landslide susceptibility evaluation is searched. When local scale segmentation is carried out, the influence of evaluation factors should be taken into account and ensure that the segmentation results are directly related to the susceptibility in some way.

Through the screening of experimental results of various methods and ideas, a Geographical Weighted Regression (GWR) model with spatial regression idea, which can link the evaluation factors and the susceptibility evaluation results, is selected as the scale segmentation model. The predecessor of Geographical Weighted Regression (GWR) is Spatially Varying- Coefficient Regression Model (SVCR), which can combine data with spatial location information with regression idea and the obtained regression parameters also have spatial location information, which can be used in geospatial analysis. The spatial heterogeneity of different location attributes can be quantified by using this model in geospatial analysis.

The geographically weighted regression method is used for local segmentation to study the relationship between the evaluation results, evaluation factors, and evaluation model parameters for different local areas. Comparison with the global scale proves that the local segmentation in this way has better evaluation accuracy.

2.3. Landslide evaluation factors were identified

In the evaluation system of landslide susceptibility, landslide evaluation factor data is the core and key to establish landslide sample data set [7]. The accuracy of the data is directly related to the reliability of the evaluation results, and whether the extraction method is scientific and reasonable also has a profound impact on the accuracy and depth of the evaluation. Both of them are key elements that cannot be ignored and need to be emphasized in the evaluation process of landslide susceptibility. In this paper, a total of 14 landslide evaluation factors, including landslide background factors and landslide inducing factors, were carefully screened and accurately extracted by drawing on the wisdom of predecessors and closely combining the fruitful results obtained by previous researchers in the study area with highly similar geological environmental conditions. To deeply analyze the spatial distribution law of landslide disasters, the frequency ratio method is further used to deeply integrate it with landslide data and a special study on the spatial distribution of landslide disasters for each evaluation factor is carried out, to provide more solid data support and theoretical basis for landslide susceptibility evaluation. The landslide evaluation factors include the following:

(1) Topographic and geomorphological factors: elevation, slope, slope direction, plane curvature, profile curvature, slope morphology, surface roughness, surface relief

(2) Geological factors: stratigraphic lithology, distance from faults

(3) Hydrological factor: distance from water system

(4) Triggers: NDVI (Normalised Difference Vegetation Index), distance from roads, distance from settlements

2.4. Application of coupled different landslide susceptibility assessment models is realised

Convolutional Neural Network (CNN) is an optimization algorithm based on the TDNN model. It is mainly used for intelligent recognition of speech and pictures. Particle Swarm Optimization (PSO) is an optimization algorithm improved from Complex Adaptive System (CAS), which is essentially an optimization process [8]. The optimization principle of PSO can be understood as follows: in a multi-dimensional space, multiple moving points, known as "particles", navigate the space following specific motion rules. After function calculations, these particles seek the Fitness Value within the space. Their movement is not only governed by the initial algorithm's rules but also influenced by their ability to "perceive" their position and relative relationship to the Fitness Value throughout the motion process. By coupling the two algorithms and utilizing PSO to optimize the selection of activation functions, the number of nodes in convolutional and pooling layers, and the number of convolutional kernels, the CNN algorithm can maximize its computational efficiency in vulnerability evaluation. This approach enhances both the accuracy and speed of the evaluation process.

In the field of landslide susceptibility evaluation, to achieve more accurate and efficient risk assessment, this study focuses on integrating intelligent algorithms with deep learning models and conducts in-depth research on the development of a PSO-CNN coupled model. We apply the PSO algorithm to the CNN model to optimize its parameters. In the landslide evaluation scenario, the attributes of each slope unit in the study area serve as the training sample dataset, encompassing detailed information on slope gradient, slope direction, rock and soil types, hydrological conditions, and other relevant factors. The PSO algorithm functions like an intelligent explorer, continuously iterating through the complex parameter space to identify the CNN model parameters that best fit the sample data. This approach not only significantly enhances the accuracy of model training and improves the precision of landslide susceptibility assessment but also increases training efficiency, saving considerable time and computing resources. Additionally, it provides strong support for the prediction and prevention of landslide disasters.

2.5. Explored the relationship between different scales and landslide susceptibility assessment models and parameter selection

To capture the differences in landslide susceptibility evaluation results at different scales, relying solely on the susceptibility zoning map is insufficient and further quantitative analysis is necessary. Therefore, this paper quantifies the differences in the evaluation results of the PSO-CNN model at global and local scales using class-specific accuracy analysis, overall prediction accuracy analysis, and receiver operating characteristic (ROC) curve analysis. Additionally, it examines the reasons for these differences, the relationship between scale and model parameters, and other influencing factors. The differences, the relationship between scale and model parameters, and other influencing factors were analyzed.

Through the analysis of the relationship between scale and landslide evaluation factors, as well as the importance of these factors in different local areas at local scales, the following conclusions were drawn:

(1) The category-specific accuracy of landslide susceptibility zoning at the local scale is higher than at the global scale across all susceptibility zones, making the local-scale assessment more precise.

(2) The overall prediction accuracy analysis indicates that the results at the local scale outperform those at the global scale, both in individual local areas and when combined.

By analyzing the relationship between spatial scale and the parameters of the landslide susceptibility assessment model, the following conclusions were drawn:

(1) The parameters of the landslide susceptibility evaluation model at the same scale have a significant impact on both the evaluation results and their accuracy.

(2) The optimal model parameters obtained by PSO vary between global and local scales, and even among different local scales. The fundamental reason for this difference is the variation in sample data across different local areas. As the PSO algorithm searches for the optimal parameters that best fit the characteristics of each dataset, the resulting optimal solutions differ accordingly.

3. Conclusion

Based on the ArcGIS platform, data from multiple sources were collected and organized, the characteristics and attributes of various data were analyzed, and 14 landslide evaluation factors were extracted by combining the relevant data in Li County. A PSO-CNN coupling model is constructed and the optimal solution of CNN model parameters is searched by PSO algorithm to improve the accuracy and efficiency of model training. Applying the multi-scale analysis method throughout the landslide susceptibility evaluation process involves dividing the evaluation scale into global and local levels, conducting an in-depth comparison of the evaluation results at both scales, and analyzing the underlying reasons for these differences.

Geographically weighted regression is proposed to address the issue of local segmentation within the study area. This segmentation ensures that landslide evaluation factors within each local area have a similar influence on landslides while minimizing the mutual influence of evaluation factors between different local areas, thereby refining the evaluation process. Various methods were used to quantify the differences between landslide susceptibility evaluation results at global and local scales, including category-specific accuracy analysis, overall prediction accuracy analysis, and ROC curve analysis. The three indices at the global scale were 61.31%, 84.44%, and 0.832, respectively, while at the local scale, they were 72.07%, 88.27%, and 0.914. The results indicate that the local-scale evaluation outperforms the global-scale evaluation, demonstrating the effectiveness of local segmentation in improving evaluation accuracy.

The influence of landslide susceptibility evaluation factors on landslides at both the global and local scales were analyzed, as well as the optimal model parameters for landslide susceptibility evaluation at different scales. The results indicate that the importance of evaluation factors at the global scale is approximately the average of their importance across all local areas. Compared to the global scale, the local scale has a smaller sample size with more consistent characteristics. As a result, optimizing evaluation model parameters through sample-based training yields improved results.

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Disclosure statement

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Integrated Services Platform of International Scientific Cooperation

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