

Spots Identification of Natural Erosion for Hakka Rammed Earth Building: Zhang Bishi Residence Case in China

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Abstract: The Hakka earth-rammed enclosed-dragon house, a distinctive architectural heritage in Lingnan region, holds immense conservation value. However, it faces numerous challenges from natural degradation and restoration complexities. This study analyzes the natural influencing factors, noting that in Lingnan, with small temperature variations, wind, rain, and solar radiation are the primary factors affecting its conservation and restoration. Using Rhino and Grasshopper, the paper analyzes wind and solar exposure conditions of Zhang Bishi's Residence, a representative case study. The simulation results align with field observations and scholarly findings, revealing that areas exposed to high wind speeds and low solar radiation suffer more severe deterioration. In contrast, the rear parts of the courtyard—shielded from wind and better lit—experience less damage. The study identifies varying degrees of natural wear across different orientations of the structure, highlighting the need for targeted protection. Based on these insights, the paper proposes a comprehensive conservation strategy from four perspectives: material composition, construction techniques, external protective measures, and long-term maintenance. This research offers a rapid, data-supported diagnostic approach for preserving rammed earth structures in humid climates and contributes theoretical and practical value to their sustainable conservation and cultural inheritance.

1. Introduction

Hakka earth-rammed dragon-encircling houses are among the most distinctive residential architectures in the Lingnan region. As a globally recognized cultural heritage of earth-rammed residence in China and beyond, their conservation and restoration research have consistently been the focus of academic attention [1-2]. The international academic community has adopted big data technologies and advanced detection methods to monitor changes in earth-rammed soil moisture in real-time, thereby obtaining data on moisture and stiffness of earth-rammed buildings to determine the extent of damage [3].

Simultaneously, scholars have tested the tensile strength and compressive stiffness of layered interfaces within the earth-rammed layers, studied and improved the material properties and construction methods of earth-rammed buildings, providing data support for the conservation and innovation of earth-rammed architectural heritage [4]. These research methods and findings exhibit certain advantages, such as high detection accuracy and abundant real-time data, which are suitable for individual building research. However, these methods often require a long-time span for data collection, highlighting the need for faster and more accurate approaches.

Employing parametric simulation for micro-environment analysis is a trend in research. Existing

achievements mainly focus on the study of the architectural scale, structure, environment, and historical development of certain earth-rammed buildings in Lingnan, as well as the natural environmental analysis of earth-rammed buildings [5]. However, there is a lack of research on utilizing simulations to enhance building conservation and restoration, particularly regarding the destructive impacts of natural climates on different points of Hakka dragon-encircling earth-rammed buildings in the subtropical monsoon climate of Lingnan, and relevant research remains inadequate cases.

Regions such as Meizhou, Heyuan, and Huizhou in Lingnan are primary areas where Hakka earth-rammed enclosed houses are distributed, representing precious earth-rammed architectural heritage [6-7]. Government departments and local organizations have also implemented some proactive conservation measures. However, these traditional earth-rammed buildings continue to suffer from natural erosion and disrepair, with wall collapses being a common occurrence [8]. This phenomenon was also revealed in detail through physical surveys. Taking Meizhou as an example, although many Hakka earth-rammed buildings have been included in provincial and municipal conservation lists, such as Huiyang's Yang Jiaofu Enclosed House, Xueyuan Ancestral Hall's Dragon-Encircling House, and Jiufu Enclosed House, the situation remains severe on-site, with issues such as unrepaired roofs, collapsing walls,

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and vigorous plant growth on earth-rammed walls (See Figure 1).

As a nationally protected Hakka rammed earth building in the Lingnan subtropical monsoon zone, the Zhang Bishi Former Residence displays significant degradation despite its protected status. This combination of architectural type and climatic context renders it a highly typical case for studying this heritage typology. Pinpointing the most prone natural erosion spots on this structure is thus instrumental for developing effective preservation methodologies for similar dwellings across the subtropical monsoon region. As the primary building material for dragon residence house, the structural stability of earth-rammed soil directly relates to their conservation and survival. The primary causes of these issues lie in damage caused by natural factors such as wind, rain, and sunlight [5]. Therefore, this study explores conservation and reinforcement strategies for Hakka earth-rammed buildings from a climato-geographical perspective.

Consequently, the research questions are established: Which points of Lingnan Hakka earth-rammed dragon-encircling houses are most susceptible to damage under the dual influence of the subtropical monsoon and irradiation climate? What effective reinforcement and conservation strategies should be adopted for these vulnerable points?

This study adopts a research approach that examines the relationship between climato-geography and building materials, by creating wind direction maps and solar insolation maps under the subtropical climate of Lingnan. By interpreting these maps in detail, we identify the vulnerable points of dragon-encircling houses' structural strength, particularly those areas prone to damage from wind and rain erosion and intense sunlight.



Fig. 1. Partial of well protected commercialized Hakka rammed earth house and the unwell protected registered rammed earth house in Lingnan (Source from the Author)

Through this study, we aim to provide new ideas and methods for the conservation and restoration of Lingnan Hakka earth-rammed dragon-encircling houses, promoting the inheritance and efficient, precise conservation of Lingnan's earth-rammed architectural culture. Additionally, this study will provide strategic references for relevant conservation workers, jointly advancing the sustainable development of the conservation and cultural inheritance of Lingnan's traditional Hakka earth-rammed enclosed houses, effectively saving conservation costs, and realizing the prosperity and development of Lingnan's architectural culture.

2. Natural erosion on rammed earth building

The primary limitations to the preservation of rammed earth architecture are the collapse and instability of the walls, which are caused by both human and natural environmental factors [9]. Human factors can resist the destruction caused by natural environmental influences. For example, the proportion of rammed earth materials, construction methods, and maintenance practices directly affect the mechanical properties of the building, such as compressive strength, tensile strength, and shear strength [10]. Natural factors are primarily geographic and climatic, including wind, rain, and solar radiation, as well as factors such as rainwater infiltration, air humidity, wind direction, wind pressure and speed, solar radiation, and plant and microbial activity [11].

Wind direction generates wind pressure effects, wind-induced vibration, wind erosion, changes in humidity, and the transmission of pollutants, all of which affect the safety, stability, and durability of the building walls [12]. Under the influence of wind, buildings and structures vibrate, causing loosening of the connections between wall materials, which in turn compromises the integrity and stability of the walls [13]. Long-term wind erosion can cause the surface material of the walls to peel off and deteriorate, reducing wall thickness and strength. Furthermore, wind erosion can accelerate the formation and development of cracks on the surface, further compromising the stability and durability of the walls. Wind-driven heavy rainfall and seasonal floods not only threaten the physical structural safety of rammed earth buildings but also exacerbate the erosion and damage to soil walls. Rammed earth walls absorb water and expand, causing cracking, disintegration, or even collapse [14]. Wind is particularly critical as it affects the angle of rainfall, which results in rainwater infiltration and surface erosion, weakening the wall's structural stiffness [15-16].

In water drip tests, the degree of erosion reaches its maximum when the rainfall angle to the horizontal plane is between 30° and 45°. In rainfall simulation tests, the deepest erosion occurs when the rainfall angle to the horizontal plane is between 15° and 30° [17]. Wind direction and solar radiation also affect temperature and humidity changes, potentially causing condensation on the surface of the walls, which increases the internal humidity of the walls, leading to mold growth, corrosion, and other issues. Additionally, humidity fosters the growth of microbial communities, and plant roots can separate from the wall, accelerating corrosion, disintegration, and collapse. Thus, wind direction and the building's coverage influence the degree of erosion of the rammed earth walls. Environmental conditions may also cause the surface strength of the wall to be higher or lower than the internal strength, with the mechanical properties of the wall being optimal when no moisture or salt-induced erosion is present [18].

The maintenance and restoration of rammed earth buildings become particularly important. Rammed earth can be preserved indefinitely in temperate climates,

where it is not exposed to natural rainwater erosion, and the temperature remains constant [13]. In contrast, the subtropical monsoon climate of Lingnan is characterized by relatively stable temperatures with small temperature variations, making the study of wind direction a key method for preventing rainwater tilting and thus exploring effective moisture-proofing and rainproofing strategies for Hakka rammed earth architecture. Solar radiation accelerates the drying of rammed earth buildings, reducing the time of rainwater infiltration, decreasing humidity, and increasing the stiffness of rammed earth [19]. Furthermore, it has a sterilizing effect, reducing the corrosion caused by mold, moss, and other organisms on the walls [20-22]. Insufficient sunlight can also lead to reduced stiffness in certain locations of Hakka rammed earth Walled Houses. Thus, analyzing wind direction and solar radiation is crucial for studying the protection and reinforcement of rammed earth buildings.

3. Protection quo of Lingnan Hakka rammed earth residence

The main Hakka settlements in Lingnan area are identified in Meizhou, Huizhou, and Heyuan, all of which lie in the East Asian subtropical climate zone. The temperature variation is small, with rare extreme weather events [23]. However, the rainy season coincides with the hot season, with rainfall concentrated from April to September, and the area is subject to typhoons. Data from 1961 to 2023 show that the relative humidity, wind speed, and sunlight hours in Guangdong have decreased at rates of 0.6% per decade, 0.07 m/s per decade, and 27.4 hours per decade, respectively. During 2023-2025, the relative humidity was high, wind speed was large, and sunlight was abundant. Since 2009, wind speed has increased. The highest annual average wind speed was recorded in 1961 at 3.1 m/s, while the lowest was in 1992 at 1.6 m/s (Figure 3). The average wind speed in 2023 was 2.1 m/s, higher than the historical average of 1.9 m/s [24].

In Huizhou, the average annual precipitation in Longmen is 2167.8 mm, with three main rainfall belts: Enping–Yangjiang, Haifeng, and Longmen–Qingyuan. The region experiences an average of 14.1 days of heavy rainfall annually, with June receiving the most (329.7 mm). Wind, sunlight, coverage, and drainage are the key factors influencing rammed earth architecture. This paper begins by studying the wind direction, rain intensity, and sunlight factors to identify vulnerable areas of rammed earth buildings and propose protection and reinforcement strategies.

Hakka rammed houses are a distinctive feature of the region’s rammed earth dwellings. The layout of traditional Hakka architecture is highly organized and symmetrical, reflecting the defensive culture and clan-based settlement patterns of the Hakka people, with high aesthetic and cultural value [25]. These rammed earth dwellings exhibit characteristics of enclosure, centripetal structure, and axial symmetry. They include various unique forms such as the horizontal house, the hall house,

the Walled House with four corner towers, and earth towers, among others.

For example, the spatial sequence of the central axis begins with the Main Entrance, followed by the Sun-grain ground, Main Gate, Lower Hall, Lower Patio, Middle Hall, Middle Patio, Upper Hall, Huatai Mound, and Enclosed Dragon Hall. The eastern section features two doors, with the easternmost door (Gate 4) aligned along the north axis leading to Patio 3, situated between the enclosed rooms and lateral rooms. The spatial sequence continues with Corridor, Patio 4, Corridor, then Huatai Mound, Enclosed Rooms (corner), and other rooms. This form of Walled House typically uses a wooden arch to extend the eaves, with the walls primarily made of rammed earth, mud brick, and blue brick. Due to the high groundwater table and the soft, easily sunken soil in the Lingnan region, coupled with the humid and rainy climate, the foundations of these buildings are often constructed using granite or red sandstone to protect the rammed earth walls.

However, Field survey results indicate that the stone materials used for the foundation are often small, ranging from 300-800 mm in size. The eaves height in front of the hall is 3.175m, with an eave’s width of approximately 1.220m. The eaves height of the circular dragon’s house reaches 6.080m, while the outer eaves width is 0.380m. The wall surrounding the Sun-grain ground stands at a height of 2.040m, with an eave’s width of 0.345m. The worst erosion is the lower base of the rammed wall, especially the corner of rear enclosed rooms in the northern part of the house (Figure 3) and the roof frame and tiles are seriously damaged.

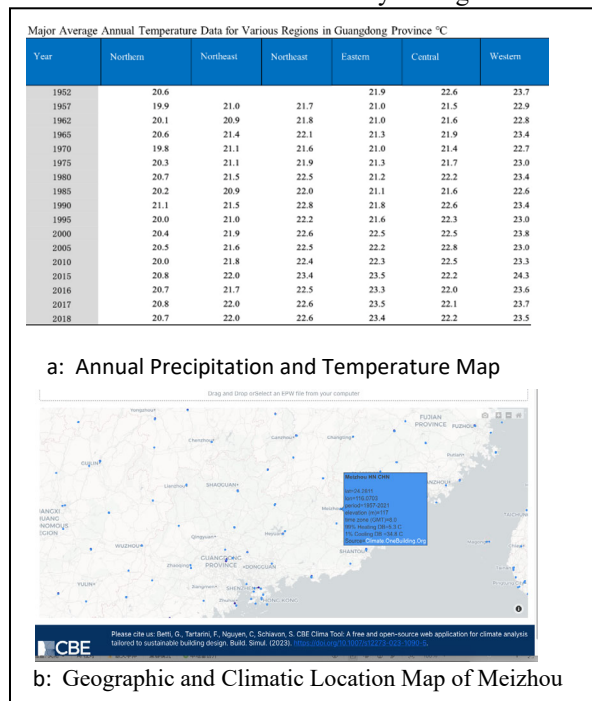


Fig. 2. a: Annual Precipitation and Temperature Map (Source from Guangdong Meteorology Service). b: Geographic and Climatic Location Map of Meizhou (Source: CBE Clima Tool)

This study will analyze the wind direction and solar radiation maps for Lingnan’s subtropical monsoon

climate, exploring the weak points in the building strength of the Walled Houses, particularly those vulnerable to damage from wind, rain, and intense sunlight.



Fig. 3. The Erosion and Protection Quo of the Hakka Rammed House (Author Source)

4. Research methodology

This study adopts a case study approach to explore the protection and reinforcement methods of rammed earth walls in Hakka Walled Houses under the subtropical monsoon climate. The research focuses on analyzing the external environmental factors—such as wind environment, humidity, and solar radiation—affecting the walls of rammed earth buildings. The selected case study is the Zhang Bishi Residence, located in Dapu Town, Meizhou City, Guangdong Province (Figure 2; Figure 4).

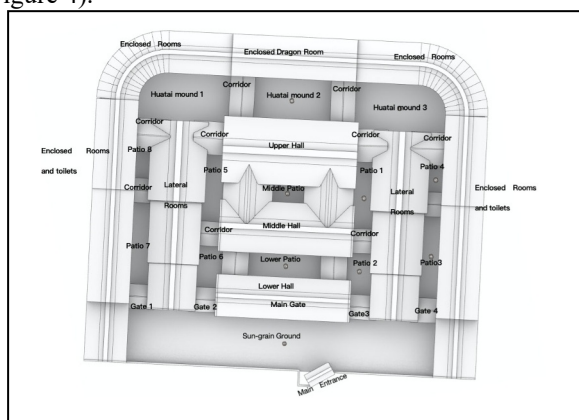


Fig. 4. The Layout Model of Zhang Bishi Rammed Residential House (Author Source)

Through a literature review, physical surveys, and measurements, geographical orientation and architectural data of the Zhang Bishi Walled House were collected. Government data reports were then reviewed for analysis, and geographic climate data for the site was obtained using Energy Plus combined with CBE Clima Tool (Figure 2). After comparing the analytical capabilities of SketchUp, 3D MAX modeling, and related plugins, Rhino software and the Grasshopper plugin with Eddy3D were determined to be superior. The Ladybug and Honeybee plugins not only provide powerful simulation capabilities but also offer more precise computation speed and visualization advantages [17, 18].

The data analysis process involved gathering building and environmental information with physical

survey and scale figures with Deli infrared rangefinder, then constructing a building model using Rhino and Grasshopper. The geographic climate environment of Meizhou was implant, and a series of calculations were performed using the Eddy3D, Ladybug, and Honeybee plugins to analyze building ventilation and solar radiation. The study analyzed the wind, sunlight, and humidity intensity at different points on the building's rammed earth walls and tested the climate data for the walls over the course of a year, visualizing the results. The analysis identified the different parts of the building most vulnerable to wind damage and provided targeted protection and reinforcement strategies, resulting in a strategy matrix for intervention.

5. Case study of erosion spots analysis based on wind environment and solar radiation

The geographical coordinates of Meizhou City are 23°23'–24°56' N and 115°18'–116°56' E, according to data from the government website, and climate data was downloaded from the CBE Clima Tool (Figure 2). to be validate, the model was experiment with two addresses, one is near the river, one is near the farm, the wind and solar radition on the same building in different location in Meizhou showed very similar.

The temperature variation in Meizhou is relatively small (Figure 2), and further processing was conducted using the Grasshopper plugin in Rhino (Figure 5). The wind characteristics of the subtropical monsoon climate zone primarily differ between winter and summer. The wind speed around the Walled House is generally low, with the prevailing winds being from the southeast in summer and from the northeast in winter (Figure 6). The left side of the figure illustrates the winter wind patterns in the subtropical monsoon climate zone, where the wind speed affects the angle of rain, which in turn influences the rainwater infiltration and surface exposure on the building [13, 16, 26, 27]. As such, wind direction impacts the building's humidity, mold, and plant decomposition, all of which affect the wall's stiffness.

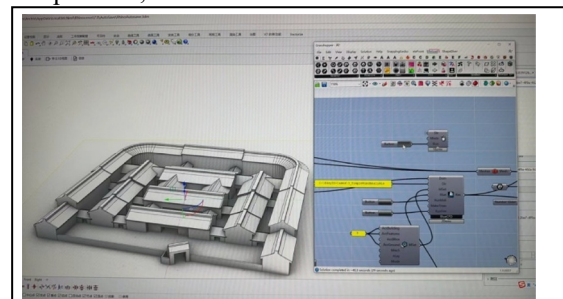
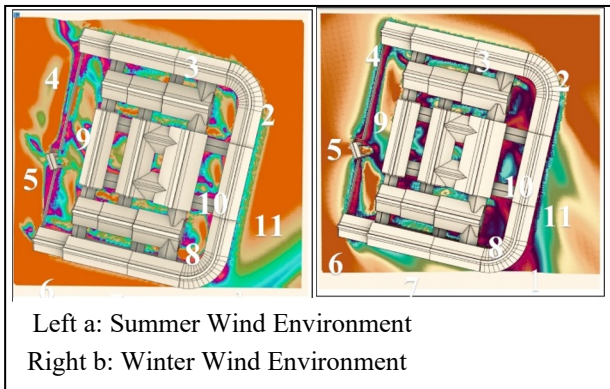


Fig. 5. The Model and Calculation Process (Author Source)

The figure shows that the maximum wind speeds occur at Spot 2, Spot 5, and Spot 6, where wind speeds exceed 2.0 m/s (Figure 6). The region is located at a lower latitude, near the South China Sea and the Pacific Ocean, and is also influenced by the terrain of the surrounding mountains. The annual average wind speed ranges from 0.9 to 2.0 m/s (Table 1). From October to

March, the prevailing winter winds are from the north, causing dryness during the winter months. From April to September, the long summer period is marked by prevailing southeast and east winds, bringing hot and humid conditions with heavy rainfall.



Left a: Summer Wind Environment
Right b: Winter Wind Environment

Fig. 6. Visual Illustration of the Wind Environment at the Former Residence of Zhang Bishi

Table 1. Wind Speed at Various Points at the Former Residence of Zhang Bishi in Summer and Winter

Wind Grade	Winter	Summer
Strong wind 1.1-2.0m/s	Spot 2, spot 5, spot 6, spot 9.	Spot 2, Spot 5 to Spot 6.
Moderate wind 0.8-1.3m/s	Spot 3, spot 4, spot 7, spot 9.	Spot 6, spot 7, spot 5, spot 4, spot 3, spot 9, spot 8, spot 10.
Weak wind 0.0-0.8m/s	Spot 8, spot 11, spot 10 and other rammed walls.	Spot 1 and the rest rammed area.

Under constant building orientation and material properties, higher wind speeds exacerbate the impact force and rain penetration intensity of wind-driven rain on walls [12-17], while increased solar radiation accelerates roof and the humidity drying effectivity relating the building erosion [19]. Based on this rationale, this study compares and evaluates the structural vulnerability points of Hakka rammed earth dwellings. Based on the solar irradiation map, areas with high annual irradiance are primarily concentrated on the southern-facing surfaces. The roofs of E1, E2, E3, E4, and E5 exhibit irradiation levels exceeding 1764 kWh/m². In the absence of obstructions, this suggests that wall surfaces in these areas are also exposed to similarly high irradiation, facilitating the rapid drying of rain-exposed walls. Wall irradiation levels in these zones range between 980–1300 kWh/m² (Figure 7). By contrast, areas E1', E2', E3', E4', E5', and E6' exhibit irradiation levels between 980–1764 kWh/m², corresponding to wall irradiation levels below 980 kWh/m². Meanwhile, inner walls at D1, D2, D3, and D4 receive irradiation ranging from 980–1300 kWh/m². Other roof and wall surfaces receive lower irradiation, around 780 kWh/m², which may hinder drying efficiency. At D4's exterior walls, solar irradiation is relatively abundant, especially at the corner labeled as Spot 1 in Figure 1. This location experiences high solar exposure, minimal wind throughout the year, and a low likelihood of rain

infiltration. Therefore, extending eaves is unnecessary to achieve effective solar drying, as the risk of wind-driven rain is low.

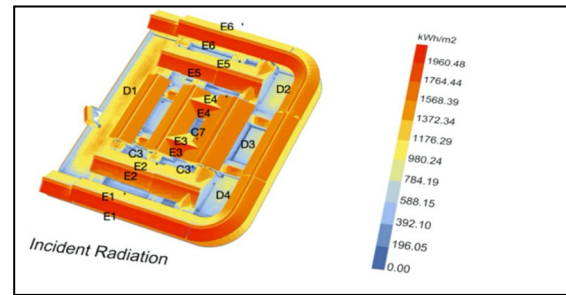


Fig. 7. Visual Illustration of Solar Irradiance Environment at Zhang Bishi's Former Residence (Author Source)

Based on these observations and data, assuming stable precipitation patterns in the Meizhou region and consistent summer rainy season climate conditions, with no changes to the roof material dimensions or building functional zones, the rammed earth walls in different areas were analyzed for natural rain infiltration damage caused by wind-driven rain. This assessment provides a basis for determining the degree of natural damage and corresponding repair levels (Table 2), enabling targeted reinforcement and restoration strategies. The analysis considers seasonal variations to guide the enhancement and protection of the structure effectively.

Table 2. Matrix of Natural Damage Levels at Different Spatial Layout Points in Zhang Bishi's Rammed Earth Dragon-enclosed House (Author Source)

House Components	Natural Impacting on Spots	Erosion Level
Rear enclosed rooms	Spot 1: Low speed both in winter and summer, little impact on rain direction. Sufficient solar radiation, with the current eave's dimensions.	Low natural damage and low repair level.
	Spot 2: Both winter and summer wind speeds are high, with solar irradiance being moderate.	High natural damage and High repair level. Main issue: Southeast wind trigger rain angle erosion, windbreaks, or shield to weak the wind is needed in summer.
	Spot 11: Low wind speeds Solar irradiance is moderate. notice that the wind speed is high about one meter near the wall in summer.	Low natural damage and low repair level. Main issue: Moderate wind, keep eave as before.
Enclosed rooms on two sides	Spot 3: High speed, Moderate wind at wall root. Moderate sun radiation	High natural damage and high repair level. Main issue: winter dry but strong wind erosion, Heavy rain, need wind shield facility or setting

	Spot 7: Low wind speed near the wall on the right enclosed rooms. High summer speed in summer. High Sun radiation.	High natural damage and high repair level in summer. Main issue: Moderate rain angle, rain roof is needed. Southeast wind trigger Rain angle erosion, windbreaks, or shield to weak the wind is needed.
Hua tai mound	Spot 8, Spot 10: Low wind speed in summer, moderate wind in summer, moderate sun radiation	Low natural damage and low repair level. Main issue: Moderate rain angle, rain roof is needed.
Sun grain ground	Spot 9: High wind speed both in winter and summer. High sun radiation.	High natural damage and high repair level: Southeast wind trigger rain angled erosion,
Other internal areas	Rammed wall of main hall, hall rooms, enclosed rooms: low wind speed, low sun radiation.	Low natural damage and low repair level. Main issue: Mold grows fast, need.
Front fence wall	Spot4, Spot5, Spot6: High wind speed around 0.5m away the wall, High sun radiation	High natural damage and high repair level. Main issue: Southeast wind trigger Rain angle erosion, windbreaks, or shield to weak the wind is needed in summer.

6. Analysis on protection and reinforcement strategy

The natural preservation and reinforcement of rammed earth buildings are mainly approached through four methods: optimization of material composition, Construction method and structural optimization, Outer Physical Protection Optimization, and Management Optimization.

6.1. Material mix optimization

Internationally, the primary focus in the natural preservation and strengthening of rammed earth buildings lies in optimizing the material mix. Traditionally, rammed earth walls often use a mixture known as "Sanhetu" composed of loess (or red soil), lime, and sand. In the Lingnan region, an additional step is taken by grinding glutinous rice into powder, mixing it with cold water, and then adding boiling water to create a thin paste. To this, brown sugar syrup and egg whites are added. This mixture is then incorporated into the prepared and finely processed sanhetu, which is then wet-rammed. This method significantly enhances the wall's toughness, resulting in an extremely hard surface once dried [20, 28]. Coastal areas, on the other hand, use river and sea sand, which is de-graveled and pounded into a semi-thick consistency for use. Due to its fiber and protein content, the resulting walls are harder and waterproof. During the Han Dynasty, horizontal wall reinforcement was introduced to strengthen structural

stability [21]. Internationally, there have also been attempts to add plant fibers, cross-placed horizontally and vertically, to improve the earthquake resistance and stiffness of rammed earth buildings [29, 30].

6.2. Construction method and structural optimization

Beyond material mix optimization, construction methods and structural optimization are also crucial for preserving rammed earth buildings. Traditional rammed earth walls have a unique anti-tilting correction system, which in modern times has been replaced with new materials. By weaving steel bars into a grid in both horizontal and vertical directions and creating T-shaped wooden frame connectors at the intersection with floor slabs, this updated structure not only addresses wall tilting issues but also enhances structural stability. Additionally, layering bamboo reinforcement is an effective method to enhance the load bearing and wind-resistance capabilities of earth walls. Bamboo rods are placed horizontally every 0.5 meters and connected with bamboo strips, forming a stable structural system [20].

6.3. Exterior physical protection optimization

The optimization of outer physical protection is vital for the durability of rammed earth buildings. Due to wind pressure effects, wind vibration, wind erosion, and the influence of wind on rain inclination, rammed earth walls are susceptible to rain erosion. Therefore, inserting a layer of horizontal bricks between each layer during construction helps resist wind and rain erosion, enhancing wall durability. Other effective protection methods include using brick or stone cladding on rammed earth walls or adopting gray bricks. By combining wall thickness, nighttime ventilation, and shading shells, the temperature during the hottest summer periods can be significantly reduced [31]. Lime-soil mortar, a protective layer made by mixing air-hardening lime with locally ground soil to produce carbonation, has gained recognition from scholars. Adding cement, lime, pozzolanic materials, and asphalt to the soil mixture is also an effective means to improve wall durability [28, 30].

6.4. Management optimization

Management optimization serves as the final line of defense in preserving rammed earth buildings. In subtropical climates with moderate to low sunlight exposure, plastic bags can achieve complete microbial inactivation within a short period of sun exposure. For intricate plant root systems on building walls, low-toxicity chemical treatments such as hexazinone and glyphosate-trichloro pyridine herbicides are used [32]. These are applied by injecting a solution into the tree roots using needles, with a dosage of 8-10 ml of 25% aqueous solution per 10 cm of tree diameter. The tree stump is then wrapped tightly in black plastic to block sunlight. In terms of protective management, regular

inspections should be conducted, and unmanned monitoring systems should be employed. Electronic humidity sensors and automatic roof covering facilities should be installed at points vulnerable to weather and sunlight damage [33-34]. Additionally, using plants or other barriers can effectively reduce wind pressure, wind speed, and rain erosion [35, 36]. Repairing eaves and roofs through physical covering and increasing the width of eaves projecting from the wall directly reduces the impact of raindrops, soaking, and bubbling. In Hakka enclosed houses, windbreak forests are often used to reduce the inclination of rain on the rear enclosed rooms, providing a protective outer layer for newly built buildings. This structure can also provide insights for the preservation of traditional rammed earth buildings [6, 37].

In the case study, a comprehensive comparison between field inspections (Figure 3) and simulated data analysis (Table 2) revealed that the locations of severe damage to the rammed earth walls on site (Figure 3) coincided with the locations prone to erosion based on simulated wind speed and sunshine calculations. Therefore, the classification of these locations was accurate. The approach of using data simulation to determine vulnerability levels is feasible. The vulnerability classification based on simulated analysis data and visual images can provide a reference for other rammed earth buildings, and the data can serve as a reference for rammed earth buildings in subtropical monsoon climate zones.

Based on a comprehensive field investigation and the research findings of international scholars, it is observed that buildings facing different directions exhibit varying degrees of erosion. The summer monsoon is the primary factor affecting rain infiltration and raindrop erosion of Lingnan Hakka rammed earth buildings. Wind also contributes to wind erosion, while solar radiation accelerates the drying of walls, reducing the duration of rain infiltration and moisture in rammed earth buildings and enhancing their stiffness.

Consequently, based on the case study locations, Spot 2 in the rear enclosed dragon house, Spot 3 and Spot 7 in the enclosed dragon houses on both sides, the internal enclosing wall and the main gate, Gate 1, and Gate 2 of the sun-grain ground's lower hall, as well as Spot 9 on the rammed earth wall of the outer enclosing wall of the sun-grain ground's front side, are all locations with high vulnerability to natural damage and repair needs. Measures such as widening eaves, installing automatic protective devices, and other flexible covering devices should be taken to cope with the rainy season in summer. On the windward side of the summer wind, i.e., the southeast direction, protective forests or other windbreak structures should be planted or built. Local stones should be added to the corners of the walls, and slope designs should be adopted to improve drainage and prevent rain and drip infiltration caused by wind.

These locations, along with others, should be protected and reinforced together, and damaged walls should be repaired using local special techniques by incorporating glutinous rice paste, brown sugar water, and egg whites into the ternary soil mixture, and

reinforcing the structure with bamboo rods as internal reinforcement. Protection and reinforcement can be carried out from four aspects: supervision and management, construction and structure, materials and proportions, and external physical protection. As a result, a strategy for the protection and reinforcement of Hakka rammed earth enclosed dragon houses in subtropical climate zones has been formulated, with a detailed matrix provided below (Table 3).

Table 3. Protection and Reinforcement (Author Source)

Strategy	Detailed method
Guardianship and Management	Establish an electronic humidity monitoring system and interactive alarm instruments and conduct regular inspections of critical areas. Conduct regular weed removal and maintenance of roof beams and tiles and perform fumigation and sterilization by covering with plastic film during periods of sufficient sunshine twice a year. Develop an automatic covering system and equip and train researchers specialized in the protection of rammed earth buildings.
Structural Strengthening for Construction:	Utilize steel mesh and T-shaped frames to replace traditional wooden components for correcting wall inclination. Employ TRM (Textile Reinforced Mortar) reinforcement to enhance shear resistance. At locations with high restoration rates and susceptibility to natural damage, add local granite and red sandstone wall enclosures for reinforcement. Incorporate horizontal brick interlayers and external brick masonry to improve resistance against rain erosion.
Material Ratio Enhancement:	Adjust the rammed earth mix by incorporating modern concrete formwork technology to enhance structural integrity and construction efficiency. Add sticky rice, brown sugar, and egg whites to the ternary soil mixture (a traditional Chinese building material consisting of clay, sand, and gravel) to boost its adhesiveness and toughness. In coastal areas, fibrous and protein-rich seabed mud and sand can be used. Incorporate cattails, reeds, or other local natural fiber materials to improve the wall's moisture absorption performance. Research into new biological additives is also conducted. Use low-content hydraulic lime to reduce biological erosion. New mixed plastering materials, such as lime-mortar mixtures, provide a durable protective layer. Reinforce walls with bamboo or brick reinforcement to increase wind resistance and load-bearing capacity. Adding asphalt to raw soil can enhance the waterproofing performance of rammed earth walls.
Physical Protection and Reinforcement on external of rammed wall	Increase wall thickness and utilize shading shells and nighttime ventilation to reduce temperature fluctuation damage. Install extended eaves and windbreak forests to mitigate the impact of raindrops' inclination and direct hits. Achieve microbial inactivation through sunlight exposure or plastic bag coverage. Establish buffer zones to slow down wind speed and enhance the wall's resistance to wind and rain.

7. Conclusion

This study analyzes the erosion patterns of rammed earth buildings significantly influenced by the wind environment; particularly where high wind speeds exacerbate wall moisture due to the oblique trajectory of raindrops. Solar irradiation aids in accelerating drying and enhancing wall stiffness, but areas with weaker irradiation experience higher humidity, conducive to mold growth and plant root infestation, further compromising structural stability. By analyzing various directional points at the former residence of Zhang Bishi, this study uncovers the protection and reinforcement patterns of rammed earth buildings in subtropical monsoon climates.

The study finds that different points, influenced by a combination of wind speed, rainfall, and solar irradiation, exhibit varying degrees of damage and repair needs. The rear enclosed dragon house (Spot 1), with lower wind speeds and ample solar irradiation, experiences minimal natural damage and only requires conventional rain shelter measures. The side enclosed houses (Spot 3, Spot 7) suffer severe rain erosion in summer due to higher wind speeds, necessitating larger eaves and additional windbreak measures. The internal enclosed house (Spot 9), while experiencing higher wind speeds, benefits from good solar irradiation and requires rain sheltering and improved drainage to enhance protection. The front enclosing walls (Spot 4, Spot 5, Spot 6), exposed to high wind speeds and abundant summer rainfall, require shielding and buffer zone designs to mitigate damage, with management also playing a crucial role. This study explores key areas for preventing natural erosion in Hakka rammed earth buildings in Lingnan and proposes a corresponding framework of response techniques.

8. Research contributions and limitations

The primary contribution of this study is its quantitative analysis of the damage mechanisms of Hakka rammed earth buildings in subtropical monsoon climates, focusing on the wind environment and solar irradiance for the first time. Theoretically, it proposes a relationship model between wind speed, irradiance, and the degree of wall damage, deepening the understanding of the climate adaptability of rammed earth buildings. Practically, the study provides specific strategies for the protection of rammed earth buildings, including differentiated repair schemes based on point variations and improvements in material technology. However, the study is limited to a simulated point analysis approach and requires more long-term monitoring and practical application of local protective materials. Future research should explore low-cost, more environmentally friendly reinforcement and protection technologies, combining traditional materials with modern methods to achieve cost-effective protection strategies.

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Disclosure statement

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