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Learning from the Past: An Analysis of the Sustainable Features of Hakka Tulou

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LEARNING FROM THE PAST: AN ANALYSIS OF THE SUSTAINABLE FEATURES OF HAKKA TULOU

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A Thesis Submitted in Partial Fulfillment of the Requirements for

The Degree of Master of Architecture

Department of Architecture

Golisano Institute for Sustainability

Rochester Institute of Technology

Date of approval: 08 May 2018
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Abstract

The Hakka tulou represent an ancient form of Chinese architecture common in Southeast China. In 2008, several of the tulou were listed as UNESCO World Heritage Sites. A tulou is usually an earthen building with an enclosed circular shape serving hundreds of residents. People have inhabited such structures for centuries due, in part, to their ability to passively moderate temperature. This particular form of architecture represents an ancient wisdom: it is a sustainable design concept that has thrived for centuries. The global energy crisis has become a problem for all. The ancient concept of the Hakka tulou, which has the potential to help save energy by providing a model for sustainable architecture, may hold some valuable answers. To establish whether modern design could be improved using the principles employed by the Hakka tulou, and whether tulou design could be improved upon by formal redesign, this thesis will create a basic model of the tulou and a modernized version thereof, before using computer software to analyze and compare their respective solar, wind and daylighting performance. It will then modify the basic tulou model by adjusting its shading and ventilation features to determine the optimal design. The model will then be compared to a standard modern design to establish whether the traditional design can be improved upon.
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1 Introduction

Buildings consume significant amounts of energy and produce high levels of CO2 emissions. According to the International Energy Agency (IEA)\(^1\), in 2015, the world’s total energy consumption was 9,383 Mtoe (million tons of oil equivalent), with residential buildings consuming 2,051 Mtoe, and commercial and public services consuming 756 Mtoe. Combined, residential and public buildings accounted for 29.92 percent of total energy consumption. Also according to the IEA\(^2\), in 2010, in the average Chinese residential building, 34 percent of energy was consumed by space heating and cooling, 40 by water heating, 16 percent by cooking, 2 percent by lighting, and 8 percent by appliances and other equipment. In the average Chinese commercial building, 53 percent of energy was consumed by space heating and cooling, 21 percent by water heating, 13 percent by lighting, and 13 percent by appliances and other equipment. Space heating and cooling, water heating, and lighting are therefore the main activities consuming energy. Reducing


\(^2\) International Energy Agency (Paris) and Organization for Economic Co-operation and Development. “IEA Sankey Diagram.”
energy consumption in these categories is critical to the creation of more sustainable buildings.

While these three activities consume the most energy, they are also most closely tied to human comfort and health. The user experience of a building is at least as important as the building’s energy performance. However, an inherent conflict exists between comfort and energy consumption. A building that has the ability to passively moderate temperature will therefore be well placed to attain both comfort and energy-saving goals.

![Figure 1.1-1 2010 Chinese Residential Building Usage](image1)
![Figure 1.1-2 2010 Chinese Commercial Building Energy Usage](image2)

Incredibly, the ancient Hakka tulou buildings in Southeast China achieved this goal of sustainability centuries ago. The Hakka tulou have the ability to passively moderate temperature without the help of any kind of modern sustainable technology, material or
theory. This has aroused people’s attention, and this thesis will analyze the environmental performance of the Hakka tulou and modify the design to establish whether it could be of benefit to current architectural practice.

1.1 SUSTAINABILITY

The term “sustainability” has been defined in a number of ways. The most straightforward of these definitions is “the ability to sustain.” The word can be applied to almost every context. Thus, we have seen the coinage of “sustainable development,” “sustainable economy,” “sustainable architecture,” “sustainable cars,” and “sustainable food.” There are even relationship guides claiming to provide the key to “sustainable love.” Sustainability has become a modern buzzword. The ultimate goal of sustainability is to sustain the existence of the human race. To do so, we must find new, renewable sources of energy, and reduce our consumption to make better use of existing resources.

As architects, we can do our part to aid humanity in the attainment of this goal by designing sustainable architecture. Such architecture uses new, innovative technology, but must also look back at history, at examples such as the Hakka tulou, which managed to achieve the goal of sustainable buildings centuries ago.
1.2 THE HAKKA TULOU

The Hakka tulou are a type of ancient Chinese architecture common in Southeast China, and form an essential part of Hakka culture. A group of 46 tulou structures located in Fujian province was listed as UNESCO World Heritage Sites in 2008. The oldest group of Hakka tulou still in existence was built in the 13th century. Tulou structures usually have between three and five floors, and the largest could hold up to 800 residents. The style of architecture was mediated by traditional Hakka culture and reflects the relationship between the Hakka people and the local environment.
1.2.1 The History of Hakka Tulou

The Hakka, an offshoot of the Han people, were originally based in the Yellow River region. In the 12th century, the Hakka, fleeing war, began migrating toward southern China. The word “Hakka” means “outsiders,” a term intended to differentiate the new arrivals from the area’s original local inhabitants. In the 13th century, the Hakka moved to the part of Southeast China now known as Fujian. In Hakka tradition, people are gathered in clan groupings, with the members of a clan living together in the same village or, in the case of tulou, in the same building. Fujian is a mountainous, forested area, and was sparsely inhabited at the time. Danger lurked in the woods in the form of wild animals and robber
tribes. To protect their clans, the Hakka developed a defensive type of residential building with fortress-like features, called the tulou, or “earthen building”, after the compacted earth that composed the exterior walls. Tulou are enclosed structures surrounding an interior courtyard, enabling clan members to engage in outdoor activities within the protective confines of the buildings. Furthermore, the buildings provided significant storage space to hold food stores for their inhabitants, allowing clan members to shelter inside their fortresses for extended periods of time, if needed. The Hekeng group of tulou (Figure 1.3-1) comprises seven round tulou buildings arranged in the shape of the Big Dipper, demonstrating the Hakka’s respect for the universe.

1.2.2 The Form of Hakka Tulou

Using shape as a distinguishing characteristic, the Hakka tulou can be classified into two general types: round and square. All Hakka tulou share a similar layout: residential units line the interior of the outer wall, and a courtyard with a water well and clan temple form the core. Circular tulou usually feature an open courtyard with the clan temple facing the gate (Figure 1.3-2). Some of the larger structures may not have the regular courtyard, instead featuring another layer of single-story buildings (Figure 1.3-7). The Hakka placed

their clan temples at the center. Forming the core of these buildings, the temples signify respect for the Hakka’s ancestry: the root of the clan is the spirit of Hakka culture. The residential Hakka tulou are usually between three and five stories high, with a kitchen on the ground floor, grain storage in the middle, and bedrooms at the top. All of the units share several public stairs, and each floor is ringed by a circular corridor on the inner side of the building. Usually, the units on the same vertical line belong to a single family. The exterior earthen walls usually have a thickness in excess of 1.5 m, for defensive purposes. For similar reasons, the first floor usually lacks exterior windows. The core of the tulou may consist of either a courtyard or further single-story buildings with public functions. Smaller tulou may retain an open central core as an outdoor area to serve as a public space (Figure 1.3-6). Some larger tulou have additional layers of single-story circular buildings with functions such as kitchens, storage areas, and pigpens. Tulou structures feature a significant amount of storage space, intended to hold food stores as a defensive feature enabling the structure’s inhabitants to survive a war of attrition or await military reinforcements.

Tulou buildings combine wooden structures and rammed earth. The earthen walls were built using rammed earth bricks that were strengthened using plant fiber (Figure 1.3-3). The wooden structures are similar to those used in other traditional Chinese architecture: the overhanging wooden roof (Figure 1.3-4), for instance, is a legacy of the Han culture,
brought to the area from central China by the Hakka’s ancestors. This structural combination uses local materials, reflecting the Hakka’s faith in self-sufficiency.

Figure 1.2-2 Courtyard of a Circular Tulou

Figure 1.2-3 Earthen Wall
Figure 1.2-4 Tulou Roof Structure

Figure 1.2-5 Interior of a Tulou
Figure 1.2-6 Ground Floor Plan of a Square Tulou
Figure 1.2-7 Ground Floor Plan of a Round Tulou
2 Hypothesis and Research Problems

The environmental problems created by excessive energy consumption have attracted widespread attention in recent years. The construction industry has joined the drive to create more sustainable products by raising standards for buildings’ energy performance. While a multitude of new materials and technologies can improve a building’s energy performance, buildings can only make use of those that are not prohibitively expensive and that are approved in time. Passive house design, which is now gaining in popularity, is nevertheless not a new concept: our ancestors have already successfully constructed buildings featuring passive sustainable designs, of which the Hakka tulou is one example.

This study takes as its hypothesis the idea that people have comfortably lived inside tulou structures for centuries because Hakka tulou have the ability to passively moderate temperature. The Hakka tulou is a centuries-old sustainable design concept.

This hypothesis gives rise to the following two research questions:

1. Can a present-day design based on the principles of the Hakka tulou improve upon tulou performance with regard to thermal comfort and daylighting?
2. Can traditional tulou design be improved upon with formal redesign?
3 Literature Review

Since several of the tulou were listed as UNESCO World Heritage Sites in 2008, tulou have drawn some attentions in the architecture field and some of the researchers focused on the suitability aspect of the Hakka tulou.

Jun Ma’s 2008 review\(^4\) of the Hakka tulou focused on their development from an ecological adaptability perspective. Ma believes that the Hakka tulou have a number of features that display their ecological adaptability:

1. *Superb choice of location:* The Hakka built their tulou on the southern side of hills, facing water. The change in elevation aids drainage, while the hill on the northern side protects the tulou from the northern winds in winter. The water on the southern side provides clearance for solar exposure, keeping the building warm in winter.

2. *Scientific in structure:* The enclosed form of the structure with its central courtyard separates the internal micro environment from the external macro environment. As a consequence, the ventilation of the structure depends mainly on the higher level air,

which is cleaner than the air close to the ground, maintaining higher air quality in the courtyard.

3. **Sustainable building material**: The Hakka tulou use stone foundations, earthen walls, and wooden interiors. All of these materials are harvested locally and with minimal environmental pollution. The tulou also use much less wood than wooden structures.

4. **Harmony with the environment**: The courtyard, which contains one or more water wells, is surrounded by water drains. The presence of these water features affects the moisture status of the micro environment in the courtyard, and the evaporation of water may help reduce temperatures in summer.

Ma also points out a number of drawbacks of the tulou, including the absence of evacuation routes, the lack of natural light in the lower parts of the building, and its incompatibility with modernization. Ma proposes maintaining the structure while modernizing the interior materials, enlarging the windows, and changing the function of the building to increase its value to modern society.

Similarly, Keith D. Lowe⁵ divides the sustainable elements of the Hakka tulou into three principal categories: material, social, and spiritual. The Hakka tulou were constructed

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using earth or mud as the main building material, with thick, enclosed walls. These walls help reduce energy consumption while maintaining a comfortable living space year-round. Moreover, the tulou are closed to the exterior and open to the interior, providing security and a social space at the same time.

In the same year, Kangsheng Tan⁶ conducted a study on the architectural space of the Hakka tulou. Tan points out that the form of tulou was influenced by both Hakka culture and historical events. Because the Hakka moved from China’s central plains to its southern region to avoid war, they developed a building form with fortress-like protective features. Creating ample space for a clan to live inside required that the scale of the architecture be relatively large. While the circular shape of the space has the advantage of saving building materials and avoiding dark spots inside the building, it also means that the structure shares a larger number of identical parts, making it easier to build.

A more recent study by Yanyan Niu⁷ researched the reproducibility of the Hakka tulou. Niu suggests that the uniqueness of the Hakka tulou lies in its cultural meaning: it is

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a medium for containing and delivering the lifestyle of the Hakka. It is essential to preserve the original tulou structure, and much remains to be done in this regard. The tulou has become an icon of Hakkan culture, and its reproduction is one means by which to facilitate the continuation of that culture in modern society. The key to the reproduction of the Hakka tulou is to maintain the ecological soundness and visual characteristics of the original building form. It is, however, critical to solve the problems inherent in the design of the original tulou while reproducing that form.

Xingqian Peng\(^8\) et al. conducted a study on wind pressure on the roofs of Hakka tulou. They ran a digital wind tunnel simulation of tulou models to establish whether and how wind damaged the building structure. They conducted separate tests on the two principal types of tulou: the more significant circular shaped building, and the less common rectangular tulou. The results showed that the circular shape has superior performance in terms of wind damage prevention.

Jiongjiong Yuan and Maoyu Ran\textsuperscript{9} conducted an investigation of the indoor thermal environment of the Hakka tulou in 2008. They selected a 16 m\textsuperscript{2} third floor south-facing bedroom in a Hakka tulou in Fujian province, Nanjin City as a test subject. The tulou in question was built using a typical rammed earth and wood structure, with a 1.6 m thick earthen exterior wall. The researchers selected two further locations as controls: the flat roof of a nearby building, and a second floor south-facing bedroom in a typical brick-and-concrete residential building, with a 0.18 m thick exterior wall, approximately 500 m away from the test subject. They conducted on-site investigations in both January and July, at the height of summer and winter, respectively, to attain the most extreme results and thereby the clearest possible conclusion. The results indicated that the tulou has a more stable and comfortable interior environment than a regular local residential building.

In 2011, Yuan, Ran and Huang\textsuperscript{10} examined the wind environment of a circular tulou. They modeled a space prototype using specialized software and ran simulations using two sets of circumstances: with opened windows and gates, and with closed windows and gates.

\textsuperscript{9} Yuan, Jiongjiong 袁炯炯, and Ran, Maoyu 冉茂宇. “Tu lou ju min de shi nei re huan jing ce shi” 土楼民居的室内热环境测试 [Interior thermal environment test of Tulou resident]. \textit{Journal of Huaqiao University (Natural Science)} 29, no. 1 (2008): 91–93.

\textsuperscript{10} Yuan, Jiongjiong 袁炯炯, and Ran, Maoyu 冉茂宇. “Tu lou ju min de shi nei re huan jing ce shi” 土楼民居的室内热环境测试 [Interior thermal environment test of Tulou resident]. \textit{Journal of Huaqiao University (Natural Science)} 29, no. 1 (2008): 91–93.
The opened prototype allowed airflow into the courtyard and increased air exchange, while the closed prototype blocked wind blowing into the courtyard, creating a more settle wind environment in the courtyard. The results indicated that tulou residents can open or close the gate to adjust airflow in the courtyard to help increase the comfort level in the tulou.

In next year, Yuan, Chen and Zhao’s research focused on the ecological adaptation of the circular Hakka tulou’s light environment. They measured several points on the Huai Yuan Lou site by way of reference and then simulated the entire building’s natural light environment using a digital model of the site. The results demonstrated that the courtyard has good natural lighting, and that the lighting in the interior of the tulou is dependent on the courtyard. The indoor spaces are brighter towards the courtyard and corridor, which form the Hakka’s main social spaces. While the top floor bedrooms lack natural light, this is acceptable since the Hakka do not frequent their bedrooms during the day. The conclusion is that the tulou’s lighting environment is matched to the traditional lifestyle of the Hakka, but does not necessarily meet the requirements of modern life.

Jing Liu\textsuperscript{12} researched the application of the tulou’s architectural form in modern architectural space design. Liu’s study focused on five distinct aspects of tulou: architectural form, site layout, building plan layout, functional layout, and the relations between people’s interaction and enclosed space. The tulou’s form was originally designed for the purposes of defense, which is not the principal purpose of a modern building. Moreover, the site and functional layouts of the tulou are designed in accordance with the traditional values of the Hakka: the most important functions, such as the ancestral temple, are placed in the center, ringed by the residential units on the outer side. In modern architectural space design, the creation of a space with a multifunctional layout such as that of the tulou could result in a clear and flexible circulation path for people movements.

\textsuperscript{12} Liu, Jing 刘静. “Tu lou jian zhu kong jian xing tai zai xian dai jian zhu kong jian she ji zhong de ying yong yan jiu” [Research on applying Tulou architecture form to modern architectural space design] Art and Literature for the Masses 7 (2015): 147.
Finally, Minoru Ueda\textsuperscript{13} performed a preliminary environmental assessment of Hakka tulou for preservation and restoration purposes. Ueda’s research into the climate data, thermal performance, and natural airflow of Hakka tulou led to the Chengqi Lou tulou being ranked “A” in the CASBEE assessment framework – a ranking similar to the LEED gold standard, according to Ueda.

4 Theory and Methods

4.1 THEORY

The conservation of energy is critical in today’s world. Sustainable architecture is the holy grail, but approaches to the achievement of sustainability vary widely. The development of a range of new technologies, materials, and design theories has led to the construction of myriad sustainable buildings. However, if we review the history of architecture, we find that some ancient buildings did an excellent job of achieving the goals of a sustainable building. The Hakka tulou is a prime example of such a building.

What makes the Hakka tulou so special and so sustainable is the culture of the Hakka people. The Hakka believe in the precept of “Tian Ren He Yi”: “Human beings are an integral part of nature.” The architectural form of the Hakka tulou reflects this spirit, creating a harmonious relationship between humans and nature. Both this spirit and this building form could be of benefit to today’s people. The Hakka tulou contain a number of sustainable features. A review and test of these can determine how they function and whether they can be improved upon. This would enable us to determine whether these principles could be applied to current architectural practices.
4.2 METHODS

To confirm the advantages of the Hakka tulou’s architectural principles, a comparative experiment was necessary. To this end, a basic tulou building model was created. In addition, a basic box form building model with an identical interior floor area was constructed. Using these two models as baselines, several modifications were applied to the tulou model to address performance changes in solar gain and airflow. All of the models were then compared in terms of their solar, wind, and daylighting performance.

The conduct of this test required software-based simulations. The construction of the requisite building models made use of the 3D modeling software SketchUp 2016 and the BIM software Autodesk Revit 2016. In the model simulation phase, the building models were analyzed using the daylighting analysis tool in Autodesk Revit, and the airflow and heat transfer simulations in Autodesk CFD 2017. The simulation results in relation to three key metrics were recorded to provide a clear picture of the building’s performance in relation to airflow speed (meters per second, or m/s), illuminance and light quality (Lux), and temperature (degrees Celsius, or °C).

Due to limited time and resources, the models stood alone in the simulation scenarios to reduce simulation complexity. The daylighting test compared interior light levels through each story of the model at a single selected date and time of solar exposure.
The Autodesk CFD test results provided data on the thermal environment and airflow inside the model. These results were compared using the temperature section and fixed-point readings. The temperature section was set at 1.5 m above the floor level of each of the models, while the fixed points are at the same location on each floor. All of the data was then processed into charts or diagrams for comparison and analysis. These are set out below.

4.2.1 Digital Models

To conduct a comparative analysis between a tulou and a current design building, two sets of digital models were created. These two models have similar floor areas and functional layouts; the main differences lie in the shapes of the buildings and their construction materials.

4.2.1.1 Typical Tulou Model

Due to limitations in time and resources, this thesis will not analyze each tulou, instead creating a model of a tulou (Figure 4.2-2) using average parameters.

Tulou come in a variety of shapes and sizes and feature a range of details. They vary from circular to square in shape, and from 23 to 73 m in diameter, with a height of between three and five stories. Smaller tulou have a single ring layout, while larger tulou may have two or more rings. The layout of windows in the exterior earthen wall differs due
to the different functional layouts behind those windows. To create a representative model of a tulou, all of these variations were amalgamated to achieve an average, typical result. In addition, it was necessary for the model to be a simplified form of a real tulou to reduce simulation complexity.

The typical tulou model used in this study was based on a circular tulou. The circular shape was selected due to its unique form, which differs most markedly from the common rectangular modern residential building. The tulou model has an exterior diameter of 45 m, similar to that of a mid-sized tulou. The courtyard of the model has a diameter of 33 m, with a single-ring layout. The floor plan (Figure 4.2-1, Figure 4.2-3, Figure 4.2-4) is partitioned into 31 sections. Following the traditional tulou functional layout, kitchen units occupy the first floor, grain storage units occupy the second floor, and living-room or bedroom units occupy the third floor. The approximate total floor area of the model is 1,768 m². The first-floor units only have windows open to the courtyard; the other floors feature windows on both sides of the building. All of the windows are uniform in size (1 m wide by 1.2 m tall) and evenly distributed, 1 m above the floor. The exterior earthen wall has a thickness of 1.2 m, the inner side exterior wall and interior walls have a thickness of 0.12 m, the roof has a structural thickness of 0.3 m, and the floors have a thickness of 0.25 m. The cross section (Figure 4.2-5) shows that the roof has a 1:2 slope, with an outer overhang of 2.5 m and an inner overhang of 3.1 m. The interior balcony/corridor on the second floor
is 1.5 m in width, whereas that on the third floor has a width of 2.7 m. The first floor has a ceiling height of 4.6 m, while the second and third floors have a ceiling height of 3.6 m.

Different materials were assigned to different parts of the model. Soil was assigned to the outer side of the exterior walls; wood paneling was assigned to the inner exterior walls, interior walls and floors; roofing tiles were assigned to the roof; and glass was assigned to the windows.
Figure 4.2-1 Typical Tulou Model – First Floor Plan
Figure 4.2-2 Typical Tulou Model – 3D View

Figure 4.2-3 Typical Tulou Model – Second Floor Plan
Figure 4.2-4 Typical Tulou Model – Third Floor Plan

Figure 4.2-5 Typical Tulou Model – Section
4.2.1.2 Typical Current Design Model

The typical current design model (Figure 4.2-8) is a proposed housing design based on tulou principles, and represents a building using average current design. The structure has a similar functional layout and building size as the tulou structure, but uses a typical square building form and concrete as its building material. This typical current design model has a similar floor area and the same floor height as the tulou model. The floor plan (Figure 4.2-6, Figure 4.2-7, Figure 4.2-9) is a square layout with a central courtyard.

The outer dimensions of the typical current design model is 38 m by 38 m, with the inner courtyard measuring 29 m by 29 m. The total approximate floor area of this model is 1,777 m$^2$. All rooms have windows on both sides of the exterior wall. All of the windows are of uniform size (1 m wide by 1.2 m tall) and evenly distributed. In section (Figure 4.2-10) shows that the exterior wall has a thickness of 0.2 m, the interior walls have a thickness of 0.1 m, the roof has a structural thickness of 0.3 m, and the floors have a thickness of 0.25 m. The balconies/corridors on the second and third floors have a width of 1.5 m. The first floor has a ceiling height of 4.6 m, while the second and third floors have a ceiling height of 3.6 m.

Different materials were assigned to different parts of the model. CMU was assigned to the exterior walls, brick to the interior walls, concrete to the floors and roof,
and glass to the windows. This choice of materials follows the typical contemporary building conventions used within the Hekeng village.

Figure 4.2-6 Typical current design model – First Floor Plan
Figure 4.2-7 Typical current design model – Second Floor Plan

Figure 4.2-8 Typical current design model – 3D view
Figure 4.2-9 Typical current design model – Third Floor Plan

Figure 4.2-10 Typical current design model – Section
5 Analysis of a Tulou and a Current Design

With the set of two digital models created, analysis of them require using the climate data from local area. The analysis including daylighting analysis in Autodesk Revit and thermal and wind analysis in Autodesk CFD.

5.1 CLIMATE DATA

Since vernacular architectures such as the tulou are optimized to the climate at their own location, it is important to simulate the building performance of the tulou using local climate data. The nearest climate data collection point is at Shanghang, about 50 km from the tulou property.

The principal factors to consider when simulating the performance of the tulou under local climatic conditions are temperature range and wind speed/direction. Other important factors include the radiation level and ground temperature. The climate data were obtained from EnergyPlus\textsuperscript{14}, with the raw data represented in the following figures (Figures 5.2-1 to 5.2-8).

Figure 5.1-1 shows the temperature range for Shanghang, Fujian, China. The monthly average mean temperature is 11–28 °C. The average low in winter is 8 °C, while the average high in summer is 32 °C. The temperature range in Shanghang is not extreme; a comparison with the comfort zone (based on the Adaptive Comfort Model in ASHRAE 55-2010) shows that there is a greater need for heating than cooling.
Figure 5.1-2 to Figure 5.1-5 show the wind conditions across all four seasons in Shanghang, where April denotes spring, July denotes summer, October denotes fall, and January denotes winter.
Figure 5.1-3 Shanghang July Wind Wheel
The wind directions in all four seasons follow a clear pattern, with winds coming predominantly from the southeast in spring and summer, and from the northwest in fall and winter. The average wind speed is between 3 m/s and 4 m/s.

Figure 5.1-6 shows the daily average dry bulb temperature curve for each month of the year in Shanghang. From May to August, temperatures peak around 3 pm, while for the remainder of the year the high appears around 4 pm. Daily temperatures are at their lowest around 8 am throughout the year.
Figure 5.1-6 Shanghang Temperature Curve

Figure 5.1-7 Shanghang Radiation Range
Figure 5.1-7 shows the solar radiation level in Shanghang. The solar radiation level directly relates to the angle of the sun. As a result, radiation levels are highest in summer and lowest in winter, with spring and fall showing moderate levels of solar radiation. For Shanghang, the data show that the average solar radiation is lower in spring than in fall, due to more cloud coverage and rainy days in spring.

Figure 5.1-8 shows the monthly average ground temperature in Shanghang. The data are given for three depths: 0.5 m, 2 m, and 4 m below the ground surface. The temperature difference throughout the year is less pronounced at greater depth.
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<th>Summer</th>
<th>Fall</th>
<th>Winter</th>
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<tr>
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<td>26</td>
<td>22</td>
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</tbody>
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Table 5.1-2 Temperature Comfort Zone Range by ASHRAE 55-2010 Adaptive Comfort Model

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<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comfort Zone (°C)</td>
<td>21.0–27.5</td>
<td>24.0–29.0</td>
<td>21.5–27.5</td>
<td>18.5–24.0</td>
</tr>
</tbody>
</table>

In order to obtain a full impression of the tulou’s annual thermal performance, the simulation picked four days during the year that are representative of the typical conditions found during the four seasons for use in the solar and wind simulations using the Autodesk
CFD software: April 15\textsuperscript{th} (spring), July 15\textsuperscript{th} (summer), October 15\textsuperscript{th} (fall), and January 15\textsuperscript{th} (winter). Here, the dates are intended only for use in the CFD software to calculate the path of the sun, and do not use the actual climate data from the dates in question. The parameters used for the CFD simulations are recorded in TABLE 5.1-1, and include the wind speed and direction, the ground temperature at a depth of 2 m, and the radiation level. The temperature curves of the simulations used are shown in Figure 5.1-9. To simplify the simulation, the relative humidity level was not considered in the simulation settings. The temperature comfort zone shown in Table 5.1-2 is determined using the adaptive comfort model in the ASHRAE 55-2010 standard. All of the parameters were selected under the guiding principle of representing a typical situation. The temperature curves, radiation and ground temperature inputs were selected from monthly average data. The wind speed and direction were selected from the monthly “most hours” data.
5.2 SOFTWARE SIMULATION RESULTS

The results set out below include the natural daylight levels and CFD (computing fluid design) simulation results of the typical tulou and typical current design models.

5.2.1 Natural Daylighting Analysis

The date for the daylight simulation was set as September 22, the autumnal equinox, to obtain a more representative result. The simulation times were set as 9 am and 3 pm. The results measure illuminance in Lux. For a better understanding of the results, refer to the recommended illuminance chart (Table 5.2-1) from GB 50034-2013\textsuperscript{15}, Chinese national standard for lighting design of buildings. The following analysis considers an illuminance of 100 Lux as the benchmark for calculating the percentage area lacking daylighting.

### Table 5.2-1 Recommended Illuminance Chart (GB 50034-2013)

<table>
<thead>
<tr>
<th>Space</th>
<th>Reference Panel and Height</th>
<th>Illuminance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living Room</td>
<td>General Task, 0.75 m, level</td>
<td>100 Lux</td>
</tr>
<tr>
<td></td>
<td>Writing, Reading</td>
<td>300 Lux</td>
</tr>
<tr>
<td>Bedroom</td>
<td>General Task, 0.75 m, level</td>
<td>75 Lux</td>
</tr>
<tr>
<td></td>
<td>Bedside, Reading</td>
<td>150 Lux</td>
</tr>
<tr>
<td>Dining Room</td>
<td>0.75 m, top of dining table</td>
<td>150 Lux</td>
</tr>
<tr>
<td>Kitchen</td>
<td>General Task, 0.75 m, level</td>
<td>100 Lux</td>
</tr>
<tr>
<td></td>
<td>Task Table, Top of table</td>
<td>150 Lux</td>
</tr>
<tr>
<td>Bathroom</td>
<td>0.75 m, level</td>
<td>100 Lux</td>
</tr>
</tbody>
</table>

#### 5.2.1.1 Natural Daylighting Analysis: Typical Tulou Model

The results show that the tulou model does not have good natural daylighting. The main reason for this is the small window size and the thick earthen wall, which creates shade. The thickness of the earthen wall creates shade on all sides of the windows; there is a very limited amount of time that sunlight is able to enter the building directly. At the
same time, the size of the windows limits the amount of indirect light that can enter the building. Due to the bunker-like defensive features of the traditional tulou, there is no windows on the outside of the exterior wall of the first floor, exacerbating the lack of light. On the second and third floors, there is barely enough daylight for bedroom use; these rooms require artificial lighting in the early morning and late afternoon. Table 5.2-1 shows the calculated percentage of interior area with an illuminance under 100 Lux.

Table 5.2-2 Typical Tulou Model – Percentage of Floor Area Lacking Daylight

<table>
<thead>
<tr>
<th>Level/Time</th>
<th>1F 9 AM</th>
<th>2F 9 AM</th>
<th>3F 9 AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of area under 100 Lux</td>
<td>81.32%</td>
<td>46.44%</td>
<td>42.97%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level/Time</th>
<th>1F 3 PM</th>
<th>2F 3 PM</th>
<th>3F 3 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of area under 100 Lux</td>
<td>80.62%</td>
<td>48.24%</td>
<td>44.82%</td>
</tr>
</tbody>
</table>
Natural Daylight Analysis

Figure 5.2-1 Typical Tulou Model – Daylight Simulation Result
5.2.1.2 Natural Daylighting Analysis: Typical current design model

The results of the natural daylighting analysis of the typical current design model (Figure 5.2-2) shows the square model to have a higher overall level of illuminance due to the thinner exterior wall creating less shade. With less shade, the windows receive more direct sunlight daily. As shown in Table 5.2-3, light levels tend to be higher in those rooms where direct daylight strikes the windows, and lower in other rooms. At the same time, there is less light on the first floor, because there is less direct sunlight in the courtyard. For the same reason, the second floor has an approximately 2 percent larger area lacking daylight than the third floor.

Table 5.2-3 Typical current design model – Percentage of Floor Area Lacking Daylight

<table>
<thead>
<tr>
<th>Level/Time</th>
<th>1F 9AM</th>
<th>2F 9AM</th>
<th>3F 9AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of area under 100 Lux</td>
<td>15.60%</td>
<td>10.16%</td>
<td>8.25%</td>
</tr>
<tr>
<td>Level/Time</td>
<td>1F 3PM</td>
<td>2F 3PM</td>
<td>3F 3PM</td>
</tr>
<tr>
<td>Percentage of area under 100 Lux</td>
<td>17.11%</td>
<td>11.10%</td>
<td>9.02%</td>
</tr>
</tbody>
</table>
Natural Daylight Analysis

September 22 9am

September 22 3pm

Level 3

Level 3

Level 2

Level 2

Level 1

Level 1

Figure 5.2-2 Typical current design model – Daylight Simulation Result
5.2.2 Solar and Wind Performance Analysis

What follows are the simulation results of the typical tulou and typical current design models using the Autodesk CFD software. The spring, summer and fall scenarios were simulated with the windows both closed and open to observe whether allowing natural ventilation would help cool the interior space. The winter scenario was simulated with closed windows to avoid heat loss through airflow. All of the scenarios used a simulation time period of 72 hours to offer a stable result. The results are presented as both thermal graphics and fixed-point readings.

Thermal graphics allow for the presentation of the results of the thermal environment of each model. The thermal graphics are cut horizontal at 1.5 m above each floor level. The temperature legends (Figure 5.3-3) for the four seasons differ to provide better resolution. The combined figures show the results at 6 am, 12 pm, and 9 pm for all three floors.
The fixed measuring points are at the same location on each floor, with two measuring points on each floor, for a total of six points in each model. The points are located at the southeast and northwest sides of the models (Figures 5.3-4 and 5.3-5). The choice of point locations took into consideration several factors: avoiding the opening on the ground floor, avoiding more than two sides of the exterior walls, and avoiding being placed in close proximity to one another. The temperature readings at those points were then gathered into charts for comparison and analysis.
Figure 5.2-4 Typical current design model – Measuring Points
5.2.2.1 Temperature Section: Typical Tulou Model

Typical tulou model with closed windows (Figure 5.2-6 to 5.3-9):

The results show that there is an overall trend towards warmer temperatures on the upper floors. Due to a heat capture effect in the central courtyard area. The spring results (Figure 5.2-6) show that most space in the model maintains a temperature range of 17–
22 °C. The results also show a delay in the temperature change of the indoor space, because the thermal mass of the earthen wall stores the energy from solar heating and slow transfers it to the interior space. In the interior of the building, the wooden walls allow more rapid heat exchange. Some wind enters through the gate, mixing the air in the courtyard.

In summer (Figure 5.2-7), the indoor temperature reaches a maximum of 32 °C. The inner side of the exterior wall and all of the windows are tinged red, which means that they are allowing a lot of heat to enter the building. Still, the earthen wall helps slow the entry of heat into the building. With the sun heating the wall around the courtyard and the ground, the airflow in the courtyard is not strong enough to remove the warm air, trapping the heat inside the courtyard and heating the indoor space. Most of the space close to the windows and the inner side of the exterior wall is therefore overheated. The first floor displays the best result among the three floors due to less direct solar exposure inside the courtyard. The second floor is still somewhat protected from solar heating, and temperatures here remain acceptable. The third floor has the most severe solar exposure, leading to the worst result in this scenario.

In fall (Figure 5.2-8), the interior of the model shows a temperature range of 20–27 °C. While fall and spring show similar daily temperature curves, fall has a higher level of solar radiation and a different wind direction, resulting in a higher overall indoor temperature. Some spaces close to the windows in the north-side rooms became overheated
after a full day of solar heating. The wind, being from the northwest, does not enter the courtyard much, allowing the courtyard to capture more heat than it does in spring.

In winter (Figure 5.3-9), the model maintains an indoor air temperature of 13–19 °C. The northerly wind does not enter the courtyard to a significant degree, allowing the courtyard to retain some heat. The earthen wall has a sufficiently large thermal mass to store heat from solar radiation during the day while slowly emitting that heat to the surrounding air. The results show that the earthen wall maintains a higher temperature than the outdoor air temperature at night. This will help reduce heat loss in winter. The third floor has a higher temperature due to solar gain from the roof.
Figure 5.2-6 Typical Tulou Model (Windows Closed) – Spring Thermal graphics
Figure 5.2-7 Typical Tulou Model (Windows Closed) – Summer Thermal graphics
Figure 5.2-8 Typical Tulou Model (Windows Closed) – Fall Thermal graphics
Figure 5.2-9 Typical Tulou Model (Windows Closed) – Winter Thermal graphics
Typical tulou model with open windows (Figure 5.2-10 to Figure 5.2-12):

The overall results of the three seasons with open windows show a wide variety of indoor temperatures. There is also more airflow transferring the heat between indoor and outdoor areas.

In the spring scenario (Figure 5.2-10), compared to the results with closed windows (Figure 5.2-6), temperatures rise more quickly during the course of the morning and the airflow allows more heat into the building during the afternoon, causing overheating in the late afternoon. It would be helpful if the windows were closed after the indoor temperature attained a comfortable level.

In the summer scenario (Figure 5.2-11), compared to the result with closed windows (Figure 5.2-7), the wind brings too much solar heat inside the building. It is recommended that the windows only be opened at night once the outdoor air temperature is lower than the indoor temperature, and closed after sunrise.

In the fall scenario (Figure 5.2-12), the northwesterly wind is unable to help cool the southern side of the building. Furthermore, the southern side of the building receives more solar exposure and less wind, leads to a higher temperature on the southern exterior wall.
Figure 5.2-10 Typical Tulou Model (Windows Opened) – Spring Thermal graphics
Figure 5.2-l Typical Tulou Model (Windows Opened) – Summer Thermal graphics
Figure 5.2-12 Typical Tulou Model (Windows Opened) – Fall Thermal graphics
5.2.2.2 Temperature Section: Typical current design model

Typical current design model with closed windows (Figure 5.2-13 to Figure 5.2-16):

Overall, this building is easier to heat by means of solar radiation than the tulou model, due to several reasons: the material of the exterior wall, the shape of the building, and the shading effects.

First, the concrete material used in the construction of the exterior wall has a much smaller thermal mass than the earthen wall. It therefore took more time to heat up the earthen wall to the same temperature as the concrete wall using the same amount of solar radiation. In winter, rapid heating is desirable; in summer, less so.

Second, the change in the shape of the building caused wind to affect the building differently. Heat loss is more pronounced in the typical current design model than in the typical tulou model. There are two main reasons for this: surface area and airflow. With the same indoor and courtyard area, the square shape has a longer perimeter than the circular shape, which means that there is a larger exterior wall surface area, allowing more heat transfer. Furthermore, air around the square model moves faster than air around the circular model, removing more heat due to the faster air movement.
Third, the shading situation in the two models diverges drastically. The typical tulou model provides excellent shading: the overhanging roof casts a shadow on the exterior wall and the very thick wall casts shadows in the window openings. On the other hand, the typical current design model does not have much shading, with only minimal shading in the courtyard.

In spring (Figure 5.2-13), the interior of the typical current design model keeps an overall temperature of 22–27 °C, while some hot spots attain as much as 30 °C. The hot spots are located around the exterior wall. On the first two floors, the hot spots are on the western side. The third floor is most severely overheated due to the additional solar gain from the roof. In summer (Figure 5.2-14), the interior temperature ranges between 30 and 34 °C, with some hot spots reaching 40 °C. The western side of the building is 2–3 °C hotter than the rest of building. In spring and summer, the western side of the building tends to get warmer, because the southeasterly wind is unable to remove the heat from the western side of the structure.

In fall (Figure 5.2-15), the overall interior temperature is 25–28 °C. In winter (Figure 5.2-16), the results show an interior temperature of 14–15 °C. In fall and winter, the eastern side of the building has a higher temperature. This is due to the wind direction; sides receiving direct wind have a lower temperature. The southern side of the building gets warmer in fall and winter because it receives better solar gain and less wind. The
northern side of the building gets warmer in spring and summer because it is on the leeward side. The ground floor has the lowest temperature due to less solar radiation and heat transfer through the ground. The second floor has a higher temperature than the ground floor due to both the top and bottom sides of the space being indoor spaces. The third floor has the highest temperature among all the floors due to solar gain from the roof.
Figure 5.2-13 Typical current design model (Windows Closed) – Spring Thermal graphics
Figure 5.2-14 Typical current design model (Windows Closed) – Summer Thermal graphics
Figure 5.2-15 Typical current design model (Windows Closed) – Fall Thermal graphics
Figure 5.2-16 Typical current design model (Windows Closed) – Winter Thermal graphics
Typical current design model with opened windows (Figure 5.2-17 to Figure 5.2-19):

Overall, the results show a trend towards significantly lower indoor temperatures in the indoor spaces facing the wind. There is a better cooling effect compared to the tulou model with open windows. Wind accesses the typical current design model more easily than it does the typical tulou model because of the typical current design model’s much thinner exterior wall.

In spring (Figure 5.2-17), the wind accesses the courtyard and helps ventilate the northern and western sides of the building. In the summer scenario (Figure 5.2-18), the wind in the courtyard pushes the warm air from the courtyard into the rooms on the northern and western sides. In fall (Figure 5.2-19), there is not much wind in the courtyard, trapping heat.
Figure 5.2-17 Typical current design model (Windows Opened) – Spring Thermal graphics
Figure 5.2-18 Typical current design model (Windows Opened) – Summer Thermal graphics
Figure 5.2-19 Typical current design model (Windows Opened) – Fall Thermal graphics
5.2.2.3 Fixed Point Readings

In the following diagrams, “Original” refers to the typical tulou model and “Square” refers to the typical current design model. The diagrams have Temperature (°C) as their vertical axis and Time (h) as their horizontal axis.

5.2.2.3.1 Fixed Point Readings: Spring

The results of the spring scenario show that the typical tulou model has a lower interior temperature than the typical current design model when the windows are closed, because the earthen wall slows down the heat transfer to the interior space. When the windows are open, the temperature curves inside the typical tulou model are gentler than in the typical current design model, meaning that the temperature inside the typical tulou model is more stable.
At the first floor’s southeastern point (Figure 5.2-20), the typical tulou model has a similar temperature curve whether the windows are open or closed, because there is no window in the wall facing the wind. The typical current design model, meanwhile, displays higher temperatures when the windows are closed.

Figure 5.2-20 Original Model and Square Model 1F SE Point Spring Temperature Readings
At the second floor’s southeastern point (Figure 5.2-21), both models have a wave-shaped temperature curve when the windows are open, and the curves follow the trend of the outdoor temperature due to the better airflow on the second floor. The typical current design model with open windows has a temperature curve shifting to the right compared to the outdoor curve; at the same time, the tulou conceptual model’s curve shifts to the left. This finding is related to the heat retention capacity of the exterior wall material: the significant heat retention capacity of the soil wall delays heat transfer between the interior and exterior of the building.
At the third floor’s southeastern point (Figure 5.2-22), when the windows are open, the tulou conceptual model has a higher interior temperature, with a very gentle temperature curve. This is because, when the wind reaches the tulou conceptual model, air moves into the building more slowly than it moves into the regular building; the air temperature is therefore affected by the earthen wall before it reaches the room. Meanwhile, the typical current design model has a wave-shaped temperature curve following the trend of the outdoor temperature, but exceeding that temperature.
At the first floor’s northwestern point (Figure 5.2-23), when the windows are open, in the typical current design model, the room exhibits slower air exchange than the room on southeastern side, with comparable solar gain. This causes this point to exhibit a higher temperature than the southeast point.
At the second floor’s northwestern point (Figure 5.2-24), when the windows are open, the readings for both models are affected by the temperature in the courtyard, leading this point to have a higher temperature than the southeastern points.
At the third floor’s northwestern point (Figure 5.2-25), the situation is similar to that on the second floor, but the overall temperature readings are higher due to the additional solar gain from the roof.

5.2.2.3.2 Fixed Point Readings: Summer

The results of the summer scenario show that the typical tulou model has lower temperature readings at the same measurement points. When the windows are closed, the typical current design model exhibits higher temperatures than the typical tulou model after
24 hours. This means that the typical current design model is more easily heated than the typical tulou model.

![1F Southeast Point Temperature graph](image)

*Figure 5.2-26 Original Model and Square Model 1F SE Point Summer Temperature Readings*

At the first floor's southeastern point (Figure 5.2-26), the tulou conceptual model has a higher temperature when the windows are open, whereas the typical current design model has a higher temperature when the windows are closed. This is because the tulou conceptual model gains more heat from air exchange than is gained from heat exchange though the
exterior wall. Conversely, the typical current design model gains more heat through the concrete exterior wall than is gained through air exchange.

![2F Southeast Point Temperature](image)

**Figure 5.2-27 Original Model and Square Model 2F SE Point Summer Temperature Readings**

At the second floor’s southeastern point (Figure 5.2-27), when the windows are open, the temperature range in the tulou conceptual model is narrower than in the typical current design model. The “Original Open” curve remains above the “Original Closed” curve, meaning that the tulou conceptual model might not benefit from natural ventilation.
At the third floor’s southeastern point (Figure 5.2-28), the “Original Open” curve stays partially above the “Original Closed” curve, meaning that the tulou conceptual model may benefit from natural ventilation if the windows are operated correctly.
The first floor’s northwestern point (Figure 5.2-29) presents the most critical situation for the typical current design model in the summer scenario: because the northwestern side is on the leeward side, it receives no direct wind to cool its exterior wall, nor is the solar gain from the courtyard side blocked. When the windows are open, in the typical current design model, air from the courtyard heated by the ground gets into the rooms, exacerbating the situation. The typical tulou model remains much cooler in this situation because there is no window in the earthen wall.
The typical current design model fares better at the northwestern point on the second floor (Figure 5.2-30) than it does on the first floor due to better airflow on the second floor and the greater distance from the hot air close to ground.
At the northwestern point on the third floor (Figure 5.2-31), the “Square Open” curve is lower than that of both the first and second floors. The “Square Closed” and “Original Closed” curves are higher than at the second floor because of the additional solar gain from the roof.

5.2.2.3.3 Fixed Point Readings: Fall

The results of the fall scenario show that, when the windows are closed, the typical tulou model maintains a lower interior temperature than the typical current design model.
When the windows are open, the typical tulou model maintains a gentler temperature curve than the typical current design model.

![1F Southeast Point Temperature](image)

**Figure 5.2-32 Original Model and Square Model 1F SE Point Fall Temperature Readings**

At the southeastern point on the first floor (Figure 5.2-32), when the windows are open, there is more air movement in the typical current design model’s courtyard than in the typical tulou model. This air movement brings outdoor air into the room. The tulou conceptual model has a gentle temperature curve because there is no window in the earthen wall.
At the second floor’s southeastern point (Figure 5.2-33), when the windows are open, the tulou conceptual model has a wider range of temperature change than on the first floor. Compared to the “Square Open” curve, the “Original Open” curve has a lower apex. The “Original Open” curve is above the “Original Closed” curve, signifying that there is an opportunity to raise the temperature of the room by opening the windows.
At the southeastern point on the third floor (Figure 5.2-34), the “Original Open” curve is gentler than on the second floor. While the overall temperature is lower than on the second floor, it is still higher than the “Original Closed” curve and lower than the “Square Open” curve. This is because the roof overhang on the courtyard side interferes with the air movement in the courtyard and slows down the air exchange in the room.
The northwestern side of the building faces the wind. At the first floor’s northwestern point (Figure 5.2-35), the cooling effect of the wind means that the “Square Closed” curve is closer to the “Original Closed” curve than on the southeastern side. Because there is no window in the earthen wall, there is limited air movement and exchange in the tulou conceptual model, resulting in the “Original Open” curve closely resembling the “Original Closed” curve.

*Figure 5.2-35 Original Model and Square Model 1F NW Point Fall Temperature Readings*
At the second floor’s northwestern point (Figure 5.2-36), the “Original Open” curve is higher than on the first floor, and the temperature range is wider. Both of these findings are due to the window in the earthen wall bringing in more air from the outside. The “Original Open” curve is gentler than the “Square Open” curve, because the window cutout in the thick earthen wall forms a channel, slowing down and heating or cooling the air before it reaches the room. Conversely, the regular concrete wall of the typical current design model does not have the same effect.
At the third floor’s northwestern point (Figure 5.2-37), the “Original Open” Curve is lower than on the second floor due to the shading effect of the overhanging roof.

5.2.2.3.4 Fixed Point Readings: Winter

In the winter scenario (Figure 5.2-38 to Figure 5.2-43), the typical tulou model maintains a higher interior temperature than the typical current design model at every measurement point aside from that at the southeastern end of the first floor.
The typical current design model shows a trend towards having higher temperatures at the southeastern side than at the northwestern side. This is due to the northwesterly wind removing the heat from the northern exterior wall faster than from the southern exterior wall. At the same time, the rooms on the southeastern side experience better solar gain than the northwestern rooms, as there is no shading over the southeastern rooms.

The typical tulou model shows a trend towards higher temperatures at the northwestern measuring points than at the southeastern ones. This is due to the protection from the wind offered by the northwestern side of the exterior earthen wall and the wood-paneled exterior wall on the courtyard side easily transferring heat gain into the room. In the room at the southeastern end, the exterior earthen wall on the southeastern side stores the heat gain and slowly transfers heat into the room, while the wood-paneled wall on the courtyard side easily loses heat. At the first floor’s southeastern end, the typical tulou model shows the worst solar gain while losing heat through the ground, so the “Original” curve is lower than the “Square” curve.
Figure 5.2-38 Original Model and Square Model 1F SE Point Winter Temperature Readings

Figure 5.2-39 Original Model and Square Model 2F SE Point Winter Temperature Readings
Figure 5.2-40 Original Model and Square Model 3F SE Point Winter Temperature Readings

Figure 5.2-41 Original Model and Square Model 1F NW Point Winter Temperature Readings
Figure 5.2-42 Original Model and Square Model 2F NW Point Winter Temperature Readings

Figure 5.2-43 Original Model and Square Model 1F SE Point Winter Temperature Readings
5.2.3 Summary of Simulation Results

The results of the software simulations show that the typical tulou model has various advantages and disadvantages. In terms of natural daylight performance, the typical tulou model performs worse than the typical current design model due to the thickness of its earthen wall and the lack of windows on the first floor.

*Figure 5.2-44 Typical Tulou Model vs. Current Design Model, spring, Second Floor*
In the solar and wind performance simulations, the typical tulou model exhibits better overall thermal performance and lower levels of internal ventilation than the typical current design model. Generally, in the spring(Figure 5.2-44), summer(Figure 5.2-45) and fall(Figure 5.2-46) seasons, the typical tulou model has a lower interior temperature than the typical current design model; the converse is true in winter(Figure 5.2-47).

*Figure 5.2-45 Typical Tulou Model vs. Current Design Model, summer, Second Floor*
Figure 5.2-46 Typical Tulou Model vs. Current Design Model, fall, Second Floor
Although the interior temperature readings show the typical tulou model to perform better than the typical current design model, there is room for improvement. Moreover, the area of natural daylighting would also benefit from changes. In the following section, therefore, we set out the results of certain modifications that were applied to the typical tulou model to establish whether the model could be improved.
6 Modifications to Tulou

Early simulations demonstrated that the typical tulou model has its advantages in terms of thermal performance, while its natural daylight performance left much to be desired. Certain modifications were therefore applied to the model, and the revised model was tested using the same method.

6.1 MODIFIED TULOU MODEL

The changes to the tulou model involved changing the form and proportions of elements, and combining various elements in addition.

![Modified Tulou Model – 3D View](image)

The modified tulou model (Figure 6.1-1) features the same layout and size as the original typical tulou model, with some modifications aimed at improving the building’s energy performance.
There are three major points of change in the modified tulou model: the addition of insulation, the addition of sunshades, and an increase in the size of the window openings and gate. Each of these modifications hold the potential to help improve the building’s performance.

The simulation results using the original tulou model showed that the earthen wall has a high thermal mass and is helpful in building performance. Keeping the earthen wall and replacing the wooden panels on the other side of the exterior wall with an insulated wall will boost thermal performance. In the modified tulou model, the exterior earthen wall has a thickness of 1.2 m plus 0.05 m of polyurethane insulation board on the inside. The inner side of the exterior walls feature polyurethane insulation and a wood stud structure with a thickness of 0.2 m, the roof has a glass-fiber-filled structure with a thickness of 0.3 m, and the floors have wooden flooring with a thickness of 0.25 m.

The original tulou has a roof overhang at the top floor, which helps reduce solar gain in summer (high sun angle) while allowing solar gain in winter (low sun angle). Adding sunshades to the first and second floors (see Figure 6.1-7) could help reduce additional unwanted solar gain, which is helpful in this warm climate. The size of the overhang is calculated by blocking sunlight with an angle in excess of 60° on the southern side. The sun shading charts obtained from the Climate Consultant software shows that 60° is a balanced choice between heating and cooling (Figures 6.1-2 and 6.1-3).
Figure 6.1-2 Sun Shading Chart – December to June

Figure 6.1-3 Sun Shading Chart – June to December
The original tulou have small window openings, and the thick earthen wall casts shade over those openings. Moreover, for security, there are no windows on the outer side of the first floor. As a result, natural daylighting in tulou structures is not very good. Increasing the window size will help increase the amount of daylight inside the building. Windows can be added to the first floor since the security function is less important in modern days. The new windows are 1.2 m wide and 1.8 m tall. Compared to the original windows, which were 1 m in width and 1.2 m in length, the new windows have 80 percent more area. The typical tulou model has a window–wall ratio of 4.57 percent on the earthen wall and 10.33 percent on the courtyard side wall. The modified tulou model has a window-wall ratio of 12.92 percent on the earthen wall and 18.88 percent on the courtyard side wall (Table 6.1-1). The additional heat lost through the larger windows is acceptable since winter conditions are not extreme in this climate.

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Original</th>
<th>Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{OS}^{*}$ (Earthen wall)</td>
<td>m²</td>
<td>1679.22</td>
<td>1605.23</td>
</tr>
<tr>
<td>$S_{OS}$ (Window)</td>
<td>m²</td>
<td>76.8</td>
<td>207.36</td>
</tr>
<tr>
<td>$R_{OS}$ (Window/Earthen wall)</td>
<td>%</td>
<td>4.57</td>
<td>12.92</td>
</tr>
</tbody>
</table>
Under some conditions, the gate of the original tulou works as a vent; however, it is not sufficiently large. Enlarging the opening of the entrance on the southern side can help increase airflow in the courtyard and help reduce heat capture in the courtyard during summer, since most of the summer wind comes from the south, while not significantly increasing airflow in winter, since most winter wind is northerly. The small gate on the first floor has been increased in size so as to widen this opening and provide airflow access to both the first and second floors (Figure 6.1-4 and Figure 6.1-5).
Figure 6.1-4 Modified Tulou Model – First Floor Plan
Figure 6.1-5 Modified Tulou Model – Second Floor Plan
Figure 6.1-6 Modified Tulou Model – Third Floor Plan

Figure 6.1-7 Modified Tulou Model – Section
6.2 SOFTWARE SIMULATION RESULTS

6.2.1 Natural Daylighting Analysis

The daylight simulation results (Figure 6.2-1) show that the modified tulou model has a much higher light level inside the building than the typical tulou model. Compare the data in Table 6.2-1 and Table 6.2-2: on the first floor, the percentage of area with illuminance under 100 Lux drops from 80.6 percent to 21.78 percent; on the second floor, this percentage drops from 48.24 percent to 28.46 percent; on the third floor, the area with a light level under 100 Lux drops from 44.82 percent to 22.35 percent.

<table>
<thead>
<tr>
<th>Level/Time</th>
<th>1F 9 AM</th>
<th>2F 9 AM</th>
<th>3F 9 AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of area under 100 Lux</td>
<td>81.32%</td>
<td>46.44%</td>
<td>42.97%</td>
</tr>
<tr>
<td>Level/Time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1F 3 PM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2F 3 PM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3F 3 PM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percentage of area under 100 Lux</td>
<td>80.62%</td>
<td>48.24%</td>
<td>44.82%</td>
</tr>
</tbody>
</table>
### Table 6.2-2 Percentage of Area Lacking Daylight: Modified Tulou Model

<table>
<thead>
<tr>
<th>Level/Time</th>
<th>1F 9 AM</th>
<th>2F 9 AM</th>
<th>3F 9 AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of area under 100 Lux</td>
<td>19.45%</td>
<td>26.70%</td>
<td>19.32%</td>
</tr>
<tr>
<td>Level/Time</td>
<td>1F 3 PM</td>
<td>2F 3 PM</td>
<td>3F 3 PM</td>
</tr>
<tr>
<td>Percentage of area under 100 Lux</td>
<td>21.78%</td>
<td>28.46%</td>
<td>22.35%</td>
</tr>
</tbody>
</table>
Figure 6.2-1 Modified Tulou Model – Natural Daylight
6.2.1 Solar and Wind Performance Analysis

What follows are the simulation results using the modified tulou model and the Autodesk CFD software. The simulation method and parameters are identical to those used with the typical tulou and typical current design models. The results are presented in two ways: thermal graphics and fixed-point readings. The thermal graphics have the same legend (Figure 6.2-2) as that used in previous diagrams. The combined figures show the results at 6 am, 12 pm and 9 pm on all three floors.

The fixed points are at the locations shown in Figure 6.2-3; each floor has the measurement points in the same locations. The location of the measurement points in the modified tulou model are therefore identical to the measurement points used with the typical tulou model.
6.2.1.1 Temperature section: Modified Tulou Model

Modified tulou model with closed windows (Figure 6.2-4 to Figure 6.2-7):

The temperature section results using the modified tulou model show some similarities to those of the typical tulou model. There is an overall trend towards the upper floors being warmer than the lower floors. The results also show the heat capture effect in
the courtyard, as with the typical tulou model, but this effect is less pronounced in spring and summer in the modified tulou model.

In the spring scenario (Figure 6.2-4), the interior temperature range is 19–24 °C. The first floor has the lowest temperature due to heat loss through the ground, while the third floor has the highest temperature due to additional solar gain from the roof. Compared to the typical tulou model, the modified tulou model shows stronger air movement inside the courtyard; thus, the temperature in the courtyard is more sync with the temperature of the outdoor environment. Some warm spots appear at the windows as a result of the larger windows providing more direct solar gain.

In the summer scenario (Figure 6.2-5), in most rooms and under most conditions, the interior temperature range is 26–32 °C. The thermal graphics show that, on the first and second floors, the exterior earthen wall is less well heated than in the typical tulou model. This means that the shading modification in the modified tulou model is effective. However, the larger windows in the modified tulou model allow more heat to enter the building. As a result, there are some hot spots around the windows, especially on the courtyard side.

In fall (Figure 6.2-6), the modified tulou model has an interior temperature range of 22–26 °C. These results are about 1 °C warmer than the results of the typical tulou model.
due to the extra heat gained through the larger windows. The increased size of the gate did not harm the heat capture effect in the courtyard.

In the winter scenario (Figure 6.2-7), the interior temperature range is similar to that of the typical tulou model: 14–19 °C. The thermal graphics show that, on the first and second floors, the exterior earthen wall is heated as much as the typical tulou model. We can conclude that the shading modification in the modified tulou model did not block the solar gain in winter.
Figure 6.2-4 Modified Tulou Model (Windows Closed) – Spring Thermal graphics
Figure 6.2-5 Modified Tulou Model (Windows Closed) – Summer Thermal graphics
Figure 6.2-6 Modified Tulou Model (Windows Closed) – Fall Thermal graphics
Figure 6.2-7 Modified Tulou Model (Windows Closed) – Winter Thermal graphics
Modified tulou model with opened windows (Figure 6.2-8 to Figure 6.2-10):

The overall results show that the modified tulou model has superior natural ventilation to the typical tulou model. This is as a result of the increased size of the gate and windows allowing more air movement. This also creates turbulence inside the courtyard and at the leeward side walls; turbulence removes more heat from the wall, increasing the temperature in certain areas, such as the northern side of the building in summer, and the southeastern side and courtyard in fall.
Figure 6.2-8 Modified Tulou Model (Windows Opened) – Spring Thermal graphics
Figure 6.2-9 Modified Tulou Model (Windows Opened) – Summer Thermal graphics
Figure 6.2-10 Modified Tulou Model (Windows Opened) – Fall Thermal graphics
6.2.1.2 Fixed Point Readings

In the following diagrams, “Original” refers to the typical tulou model, “Square” refers to the typical current design model, and “Modified” refers to the modified tulou model. The diagrams have Temperature (°C) as their vertical axis and Time (h) as their horizontal axis.

6.2.1.2.1 Fixed Point Readings: Spring

The spring results show that the modified tulou model has a higher overall interior temperature than the typical tulou model, and a lower overall interior temperature than the typical current design model. When the windows are open, the modified tulou model has better air movement than the typical tulou model, leading to greater temperature variation inside the building.
At the first floor’s southeastern point (Figure 6.2-11), the results show that the “Original Closed” and “Modified Closed” curves are nearly identical. This means that the performance of the modified tulou model was nearly the same as that of the typical tulou model at this point. The trend of the “Modified Open” curve follows that of the outdoor temperature, but with a delay due to the thermal capacity of the earthen wall.
At the second floor’s southeastern point (Figure 6.2-12), the “Modified Closed” curve is about 1 °C higher than the “Original Closed” curve and about 2 °C lower than the “Square Closed” curve. This is because the larger windows in the modified tulou model receive more direct solar gain than the typical tulou model, and the earthen wall stores the heat, keeping the temperature lower than that in the typical current design model. The “Modified Open” curve is lower than the “Original Open” curve, which means that the air movement in the modified tulou model is more fluent than in the typical tulou model. As a
result, the air has less opportunity to be heated by the earthen wall before entering the building.

At the third floor’s southeastern point (Figure 6.2-13), the “Modified Open” curve is lower than the “Square Open” curve and shifts towards the right side of the diagram. This is because the earthen wall delays the heat transfer between the inside and outside of the model.
At the northwestern point of the first floor (Figure 6.2-14), the “Modified Open” curve shows a wave shape, meaning that there is good ventilation in the room: air from the courtyard is able to enter the room and then move to the exterior of the building.
At the northwestern point of the second floor (Figure 6.2-15), the “Modified Open” curve is partially lower than the “Original Open” curve, meaning that the courtyard temperature in the modified tulou model is more volatile than in typical tulou model. The shape of the “Modified Open” curve means that, while some heat capture effect remains in the afternoon, the heat is flushed during the course of the night.
At the third floor’s northwestern point (Figure 6.2-16), the results are similar to that at the second floor’s northwestern point. The shape of the “Modified Open” curve on both the second and third floors is due to the strong airflow in the courtyard.

6.2.1.2.2 Fixed Point Readings: Summer

In the summer scenario, when the windows are shut, the modified tulou model has an interior temperature lower than that of the typical current design model, and slightly higher
than that of the typical tulou model. When the windows are open, the “Modified Open” curves have the lowest low points, aside from that of the “outdoor” curve. This means that the modified tulou model has the potential to keep the interior temperature lower, provided the windows are properly operated. The typical current design model shows a higher interior temperature than the other two models.

![1F Southeast Point Temperature](image)

*Figure 6.2-17 All Models 1F SE Point Summer Temperature Readings*

At the first floor’s southeastern point (Figure 6.2-17), the “Modified Open” curve shows that, between 5 am and 10 am, the interior temperature with open windows is lower
than with closed windows in the modified tulou model. Opening the windows during this time will boost the efficacy of the modified tulou model.

Figure 6.2-18 All Models 2F SE Point Summer Temperature Readings

At the second floor’s southeastern point (Figure 6.2-18), the “Modified Open” curve shows a longer period of time with a lower temperature than the “Modified Closed” curve: the period extends from 2 am to 11 am. The “Original Open” curve is always above
the “Original Closed” curve, meaning that the typical tulou model is unable to cool down by opening the windows.

![Temperature Graph](image)

*Figure 6.2-19 All Models 3F SE Point Summer Temperature Readings*

At the southeastern point on the third floor (Figure 6.2-19), the “Original Open” curve is partially below the “Original Closed” curve, but the lowest temperature on the curve is not as low as the lowest on the “Modified Open” curve. The time period during which the “Original Open” curve is below the “Original Closed” curve is 5:30 am to 1 pm.
In contrast, the time period during which the “Modified Open” curve is below the “Modified Closed” curve is 12 am to 11 am.

At the first floor’s northwestern point (Figure 6.2-20), the modified tulou model performs much better than the typical current design model, but not significantly better than the typical tulou model. The “Modified Open” curve is wave-shaped; the wind brings the outdoor temperature into the building and changes the temperature inside the building,
while solar radiation reflects from the ground, contributing to the increase in the air temperature. The “Original Open” curve is almost flat: because there is no window in the earthen wall, there is not much airflow.

Figure 6.2-21 All Models 2F NW Point Summer Temperature Readings

At the second floor’s northwestern point (Figure 6.2-21), the “Original Closed” curve is almost identical to that on the first floor. At the same time, the “Original Open” curve is 1 °C higher than on the first floor. Thus, the two second-floor curves are nearly
identical, meaning that there is no potential to cool the room by opening the windows. The “Modified Closed” and “Modified Open” curves are 1 °C higher than on the first floor. Between 3:30 am and 12 pm, the “Modified Open” curve stays below the “Modified Closed” curve, meaning that there is potential to cool the room by opening the windows.

Figure 6.2-22 All Models 3F NW Point Summer Temperature Readings

At the third floor’s northwestern point (Figure 6.2-22), the “Modified Close” curve is 2 °C higher than the “Original Open” curve, and 1 °C lower than “Square Closed” curve,
with a lower likelihood of being elevated than the other two. The shape of the “Modified Open” curve also shows that, between 1 am and 12 pm, the interior may be cooled by opening the windows.

6.2.1.2.3 Fixed Point Readings: Fall

In the fall scenario, the solar radiation level and the daily temperature are only a little lower than in the summer scenario, but the wind direction is northwesterly, in almost direct contrast to the conditions in the summer scenario. The change in wind direction has a greater influence on the modified tulou model than on the other two models, especially inside the courtyard and on the southeastern side of the building.
At the first floor’s southeastern point (Figure 6.2-23), the “Modified Closed” curve is 1 °C lower than the “Original Closed” curve, with a gentle, smooth shape. The “Square Open” curve has a wave shape but exhibits a smooth change in temperature. In contrast, while the trend of the “Modified Open” curve follows that of the outdoor temperature, the curve is not smooth. The sudden changes in temperature indicate the presence of irregular airflow inside the room. This is because the larger openings on the exterior walls allow wind to pass through the northwestern side of the building and enter the courtyard. The wind distributes into different rooms and converges in the courtyard. When added to the
pulling effect at the gate cutout, this creates turbulence inside the courtyard. The turbulence removes more heat from the exterior wall and keeps the courtyard at a higher temperature, creating irregular airflow through the southeastern rooms.

![Figure 6.2-24 All Models 2F SE Point Fall Temperature Readings](image)

At the second floor’s southeastern point (Figure 6.2-24), the “Modified Open” curve performs in a similar manner to that on the first floor, while being approximately 2 °C higher.
At the third floor’s southeastern point (Figure 6.2-25), the “Modified Open” curve has a peak 2 °C higher than that on the second floor. The results suggest that, in the fall scenario, the modified tulou model should close the courtyard-side windows on the southern side of the building to avoid overheating the interior.
At the first floor’s northwestern point (Figure 6.2-26), the larger windows of the modified tulou model provide constant airflow from the outside and give the potential to control the interior temperature by operating the windows at different times of day.

*Figure 6.2-26 All Models 1F NW Point Fall Temperature Readings*
At the northwestern point on the second floor (Figure 6.2-27), the “Modified Open” curve has the same shape as that on the first floor, while being 1–2 °C higher.
At the third floor’s northwestern point (Figure 6.2-28), the “Modified Open” curve closely follows that of the outdoor temperature, signifying that this room has constant ventilation.

6.2.1.2.4 Fixed Point Readings: Winter

In the winter scenario (Figure 6.2-29 to Figure 6.2-34), the modified tulou model has an overall interior temperature similar to that of the typical tulou model, and higher
than that of the typical current design model. The modified tulou model has a higher interior
temperature at the southeastern end than at the northwestern end, and a higher interior
temperature on the second floor than on the other floors.

On the first floors, both of the “Modified” curves at the southeastern and
northwestern measurement points peak around 6pm, whereas the “Original” curves only
do so at the northwestern end. This is because the modified tulou model benefits from its
larger windows, which provide it with superior solar gain at the southeastern side compared
to the typical tulou model.

On the northwestern side, the measurement points in the modified tulou model
show a lower interior temperature than on the southeastern side, close to that of the typical
tulou model. This is because the northwestern side of the building receives less sun
exposure than the southeastern side. While the larger windows of the modified tulou model
loses more heat at night, the insulated courtyard side wall helps reduce heat loss through
the wall. On the third floor’s northwestern side, solar gain is reduced by the overhanging
roof on the inner side, causing the temperature to rise more slowly than in the typical tulou
model.
Figure 6.2-29 All Models 1F SE Point Winter Temperature Readings

Figure 6.2-30 All Models 2F SE Point Winter Temperature Readings
Figure 6.2-31 All Models 3F SE Point Winter Temperature Readings

Figure 6.2-32 All Models 1F NW Point Winter Temperature Readings
Figure 6.2-33 All Models 2F NW Point Winter Temperature Readings

Figure 6.2-34 All Models 3F NW Point Winter Temperature Readings
6.2.2 Summary of Simulation Results

The results of the software simulations show that the modified tulou model has various improvements. In terms of natural daylight performance, the modified tulou model performs much better than the typical tulou model due to the enlarged windows, but still not as good as the typical current design model due to the thickness of the earth wall naturally cast more shadows.

In the solar and wind performance simulations, the modified tulou model exhibits better overall thermal performance and better ventilation performance than the other two models. Generally, with closed windows, in the spring (Figure 6.2-35) and fall (Figure 6.2-37), modified tulou model have a higher interior temperature than typical tulou model, which provides overall better thermal comfort. In summer (Figure 6.2-36) and winter (Figure 6.2-38) modified tulou model performs similar or somewhat worse than typical tulou model at different spots in the building and perform much better than the current design model. It could be seen that modified tulou model performs very different with deferent windows stats. The enlarged windows increased air exchange between interior and outside of the model. The enlarged gate also allows more air movements in spring and summer, but not effect much in fall and winter.
Figure 6.2-35 Comparison between all models, spring, second floor

Figure 6.2-36 Comparison between all models, summer, second floor
Figure 6.2-37 Comparison between all models, fall, second floor

Figure 6.2-38 Comparison between all models, winter, second floor
7 Conclusion

The results of a set of computer simulations show that the Hakka tulou does have the ability to passively moderate temperature. While it demonstrates superior thermal performance to regular concrete buildings, it has low levels of natural daylight.

In the spring, summer and fall simulation scenarios, the typical tulou model has a lower interior temperature than the typical current design model. In the spring scenario, the typical tulou model has an interior temperature close to the bottom of the comfort zone and sometime a little below it, while the typical current design model falls in the comfort zone. In the fall, the typical tulou model has an interior temperature close to the bottom of the comfort zone, while the typical current design model has an interior temperature close to the top of the comfort zone, occasionally exceeding it. In summer, the typical tulou model has a greater number of hours that fall into the comfort zone than the typical current design model. In the winter simulation scenario, the typical tulou model has a higher interior temperature than the typical current design model, which is closer to the comfort zone. This result shows that the typical tulou model could provide a better interior temperature when conditions in the outdoor environment are more extreme. The typical tulou model therefore offers better thermal performance than regular buildings.
The natural daylighting conditions in the typical current design model are superior to those in the typical tulou model. Although the two models have the same window size, in the typical tulou model, the thickness of the earthen wall creates a shading effect at the window cut-outs. This effect limits the amount of light that can enter the building. Furthermore, the first floor of the typical tulou model only has windows on the courtyard side, and no windows on the outer side of the earthen wall, due to its original function as a fortress, which is no longer either necessary or useful in the modern life.

The simulation results using the typical tulou and typical current design models demonstrated that the tulou have good thermal performance, provided by its earthen wall and circuital shape, but poor natural lighting. Moreover, the interior temperature in the spring and fall scenarios are lower than is optimal. By modifying the original Hakka tulou format with altered shading and ventilation, its natural daylight and thermal performance could be improved.

In the spring and fall simulation scenarios, the modified tulou model shows an overall interior temperature that is higher than that of the typical tulou model and lower than that of the typical current design model. The results show that the modified tulou model keeps the interior temperature closer to the center of the comfort zone, signifying better thermal performance than the other two models. In the summer and winter simulation scenarios, the modified tulou and typical tulou models each have their own gains and losses.
at different measurement points, but exhibit similar overall levels of thermal performance. The results also show better airflow in the modified tulou model than the typical tulou model when the windows are opened. The thermal performance of the modified tulou model can be improved by properly operating the windows. This feature requires further research. The simulations also did not include internal heat gain, which must be studied in future.

The results indicate that the circular shape of the building and the earthen wall material of tulou structures improve building performance. These features could be considered in modern architectural practices. The hollow circular shape provides good solar gain all around the building, in addition to conserving building material while producing a structure of the same interior area. The earthen wall built with rammed earth bricks is a sustainable construction method; the material can be harvested locally to save energy in transportation, and requires no industrial treatment. Furthermore, it has been proven that earthen walls exhibit good thermal performance. One significant drawback is that the thickness of the earthen wall requires more space than a regular concrete structure wall, this mean that the application of this method is limited to rural areas.

Much remains to be discovered regarding the Hakka tulou. Additional simulations could be run using the tulou model in other climates to establish whether the tulou structure could be adopted in other locations. Tulou structures also encourage social sustainability –
the inward-facing building form can gather its residents together, creating more human contact in a modern world that is increasingly isolating. The wisdom of our ancestors is still of benefit today; by learning from the past, we can create a better future.
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