The Application of Precision Measurement in Historic Building Conservation: Taking Guanxing Tai, a historic Chinese Observatory, as an Example

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Keywords: Guanxing Tai, Precision Measurement, Total Station, Historic Building Conservation

Abstract:
Guanxing Tai, the ancient Observatory in central China, built in the 13th century as a national facility for astronomical observations, served the dual purposes of an astronomical building and an astronomical instrument as well. For a long time, many historians and astronomers attribute the Observatory's somewhat peculiar design to special astronomical numeric values like the solar elevation angle. Besides, the askew brick joints in this old brick-made building make heritage conservation experts doubt the stability of its foundations. By means of total station survey system, close-range photogrammetry and geophysical survey, we have collected precise information about its exterior and inner structure, and gradually unraveled the mysteries about the ancient building through GIS analysis and computer simulation. Our tests rule out the connection between its design and astronomical numeric values, enable us to propose a new view, i.e. the peculiar architectural style may be the result of ancient craftsmen's unconscious brick-laying acts in two directions, and invalidate the conclusion of the seemingly unstable foundations. Our new findings also provide us with more clues as to the brick processing techniques in ancient China.

1. Overview, History and Value

The Guanxing Tai Observatory is the earliest one of its kind so far extant in China, and is also one of the earliest buildings for astronomical observation in the world. Located 15km southeast of Dengfeng City, Henan Province, it is a World Heritage Site, one of the Historic Monuments of Dengfeng in "The Centre of Heaven and Earth".

In fact there is a building cluster around Guanxing Tai, built on a plot of 0.59 hm^2 and with a floor area of 657.41 square meters. With the Observatory as the core, there is a small stone astronomical instrument of the Tang Dynasty and some other buildings of the Ming and Qing dynasties. This paper only focuses on the Observatory.

The Observatory was built during Zhiyuan period (1276-1279) in the Yuan Dynasty. Guo Shoujing, a famous astronomer at that time, carried out a large-scaled astronomical observation with the support of the government. A total of 27 observatories were built throughout China, seven being large. However, only two of them have been preserved today: one is in Beijing with the name Guanxiang Tai, and the other is the building in Dengfeng which we are talking about. The Ming Dynasty witnessed major renovations of Beijing Observatory, making it significantly different from what it had been in the Yuan Dynasty. Fortunately, Dengfeng Observatory has retained its original appearance in the Yuan Dynasty, providing precious historic information to us.

There are profound historical reasons for Guo Shoujing to build a central astronomical observatory here. In the early period of Chinese civilization, people believed the place was the centre of Heaven and Earth. In the 11th Century BC, Duke of Zhou, a chief vassal highly venerated in Confucianism, led his subordinates to build the capital here, and made it the national centre point for astronomical observation and divination. The Tang Dynasty also witnessed frequent astronomical activities and took the place as an important observation station. The extant stone astronomical instrument Gui Biao is a physical evidence of the events then, and is regarded as a monument by later generations. Though astronomers in the Yuan Dynasty might cease to believe the place was the Centre of Heaven and Earth, they still took it as an important astronomical base due to its location in the heartland of China and its importance in the astronomical field as a long-term observation facility.

Figure 1: Northern facade of Guanxing Tai

From the exterior, the Observatory looks like a grey brick-structured truncated pyramid featuring obvious large lower part and small upper part, two flights of staircase made of brick and stone were set up symmetrically north of the Observatory, leading to the platform spirally. In ancient China, south was mostly taken as the architectural facade, however, the Observatory took the opposite. This was needed by observing the shadow cast by the sun: The sun shines from south, casting shadow in the north. Therefore, the major site for observation is located in the north: North of the Observatory is a groove with an iron bar on top. The bottom of the groove extends northwards on the ground and forms a stone water cistern named Gui paved with 36 blocks bearing scales on both sides, which is the measuring instrument of the sundial. In ancient China there was a widely used sundial of small size, called Gui Biao. The Observatory is essentially a Gui Biao instrument five times its usual size; thus it is a building and concurrently a large astronomical instrument. At present, historians of astronomy hold two views on the “astronomical instrument-cum-building”: one is that it was inspired by the astronomical achievements of Arabian astronomers, and the other is that it was a natural development of ancient Chinese astronomy.

The paper will not talk much about the origin of the Observatory's style. Anyhow, Guo Shoujing and his partners compiled Shoushi Calendar (Season Granting Calendar) by making use of the sundial-cum-observatories, which was the most advanced calendar in the world at that time and was 301 years earlier than the European Gregorian Calendar, which has a similar accuracy. The length of the tropical year was determined to 365.2425 days, with a difference of only 26 seconds compared with the modern astronomical measurement. As an important witness to the astronomical activity of humanity, the Observatory has great historical and scientific values.

2. Doubts

The time-honored Observatory has attracted the attention of historians and astronomers, as well as local residents.

According to the research and conjecture of modern astronomers, the Observatory works basically in the following way: An iron bar is put horizontally on the top of the platform, about 10m from the ground; at 12:00 every noon the shadow of the iron bar is cast on the water cistern on the Gui; the water cistern are filled with water to keep its levelness; an iron sheet with holes floats on the water surfaces, which significantly narrows down the otherwise thick shadow of the iron bar according to the theory of pinhole imaging; by recording the readings concerning the shadow and by geometric calculation, the solar elevation angle is attained every noon. The high platform could also make observers closer to the starry sky at night to facilitate them to conduct more astronomical observations with some instruments. Regrettably, as many astronomical instruments used in ancient China have been failed to be handed down, we have no way to get more information.

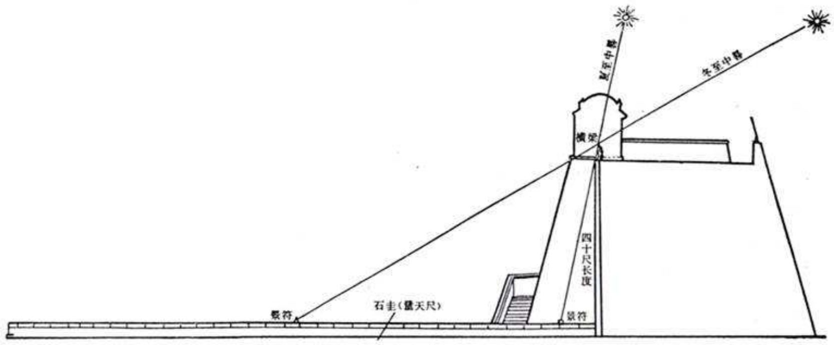

Figure 2: Observatory as a astronomical instrument Gui Biao

The observation process of the shadow cast by the sun has been restored and proved through astronomers' experiments, but people believe that as a scientific and technological building, its design undoubtedly shows its close relationship with astronomy. In many records and books about the Observatory, it is believed that the angle in which it tapers from bottom to top is probably related to the solar elevation angle, i.e. to ensure that the Observatory has no shadow at noon. Local people even call it the shadowless platform.

Moreover, we can see that the top of the platform is uneven from the north elevation, instead, the middle is higher than the other two sides; the northern groove is large in upper part and small in lower part; the spiral staircases are of complex style. We can't help doubting that whether it was specially designed for constructors' mysterious objectives of astronomical

research. We can't explain them nowadays for we haven't begun the study in this regard.
The above-mentioned views have been quoted in many serious books of astronomical history, but they are just doubts rather than judgments. If the above-mentioned views are somewhat related to legends, the following are more serious challenges and doubts.
Architectural historians may have the following doubts:
First, what kind of order was followed during the construction of the Observatory? Was the central platform built first before it was enclosed by a flight of steps, or were the central platform and the steps built from the bottom to the top at the same time?
Second, according to research results available so far, grey bricks were widely used in buildings in the Ming Dynasty in China. For example, the well-known Great Wall mainly used rammed earth before the Ming Dynasty, and was not covered with grey bricks until the Ming Dynasty. Was the brick-structured exterior of the Observatory what we see today rebuilt in the Ming Dynasty? Was it different from its appearance in the Yuan Dynasty?
Heritage conservation engineers may have the following doubts:
We can see clearly from the exterior that brick joints on the northern, eastern and western sides of the Observatory are askew. Does this mean the building foundations have the problem of asymmetrical subsidence?
Bricks have cracks on the exterior of the Observatory, and some are long. Does this indicate overall cracks of the Observatory or a serious risk in structural stability?
In sum, there are mysteries surrounding the Observatory. Some are related to interesting stories, and precious values and historic information of cultural heritage, while others are serious challenges facing architectural historians and conservation engineers.

3. Measurement and Analysis

From the early 16th century to the late 19th century, the Observatory had undergone six major or minor repairs. In 1975, a major restoration was conducted according to heritage conservation standards. As for the new problems and risks challenging the Observatory, heritage managers began a new round of restoration. The team I work with undertook the planning and design of the restoration, thus winning a precious opportunity to lift the veil surrounding the Observatory.
In fact, the above-mentioned doubts need resolving before the conservation. To properly protect the historic architecture, we shall have a precise understanding of it, which depends on accurate measurement, scientific test, and in-depth analysis. This can be divided into the following parts:
Exterior appearance: precision measurement of the size and the form;
Structure and construction;
Building material: ingredient, year and mechanical performance of the brick.

3.1 Mapping of the exterior appearance

We have already had two batches of mappings and photos about the Observatory. The first refers to the survey reports by the Society for Research in Chinese Architecture in 1937, and the second the construction drawings of restoration in 1975. The two batches are based on traditional manual measurement. As a result, the accuracy and precision were limited, even major deviation of the basic form.
We adopted the total station survey system as the technical platform for the mapping. We

have set up 32 benchmarks to measure 19 stations, gaining data about 1,153 points. Besides accurately measuring the large size, we traced the deformation of some brick joints.

We collected the following data after correcting the direction: the northern side of the outer-layer platform is 16.444m wide, the southern side 16.578m wide, the eastern side 16.500m long, the western side 16.566m long; the northern side of the inner-layer platform is 8.420m wide, the southern side 8.194m wide, the eastern side 8.107m long, the western side 8.140m long. The plan of the outer-layer platform is nearly in the shape of square, while the top of the inner-layer platform has the eastern and western sides extended outwards, making a slight expansion of the mouth of the northern groove.

In the elevation, the northeast ridge of the Observatory is 9.235m high, the northwest one is 9.335m high, and the groove is 9.418m high. These data were not included in the height of eaves.

The extended lines of the eight ridges can't meet at a certain point in the plan or in the elevation. After the restoration of the eastern part in 1975, the angle between the two ridges of the inner-layer platform was changed, so we made no research on it. The western part has retained its historic appearance, and there are different angles between the four ridges and the 45 degree angle line.

3.2 Structure and construction

This involves in two components: the platform, and the base & foundations. They adopted the same technical methods: ground-penetrating radar, Rayleigh wave, refraction survey, and other geophysical methods.

To check the geophysical data, the engineers proposed to punch horizontally in the hidden part and vertically in the nearby part of the platform so as to collect samples for testing, which can help verify the state of the inner platform and the foundations. However, the proposal was denied after the discussion of heritage managers and the experts' advisory team. Finally, we dug an exploratory trench and get some samples during the dismantling of an abandoned school 50m east of the Observatory. Though it can't provide direct data about the base of the Observatory, we can have a more precise understanding of the geological state in its surrounding area.

3.3 Building material

It includes adopting the thermoluminescence technology to make age-dating of the brick, adopting chemical methods to analyze the ingredient of the brick, and conducting static damage test to check the remaining dynamic performance of the brick. On the premise of no damage to the historic architecture, we collected few samples by ways of picking the fallen and broken fragments or selecting the replaced pieces during the last restoration in the rear courtyard.

I won't talk much about the ingredients and dynamic performance for they have no direct relationship with the problems discussed in this paper. We have gained satisfying results in the age-dating, and I will talk about it in the following part.

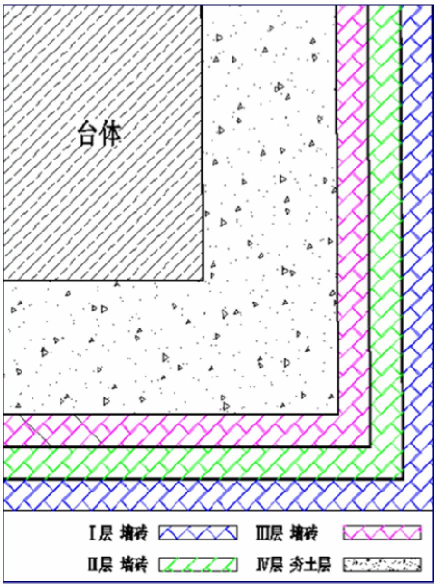

Figure 3: Structure of Guanxing Tai

4. Resolve mysteries and correct misrepresentations

Based on the above-mentioned work, we made in-depth analysis to resolve the mysteries and doubts about the Observatory.

4.1 Peculiar design vs. special astronomical numeric values

We find an interesting phenomenon when transforming the coordinates of 1,153 observation points into a 3D model and running simulation of the whole-year sunshine according to the latitude of Dengfeng City in GIS to observe the shadow of the Observatory. That is, in early June to late July every year, the sun shines straight on the northern side at 12:00 at noon, but there is no shadow all day long on the summer solstice.

According to the popular view that the Observatory is a shadowless platform, its contraction degree corresponds to the solar elevation angle, the correspondence between the simulation of the sun shadow and the date shall be more regular. In fact, we can conclude by simple geometrical theory that the platform has no shadow at noon in any day of the year as long as its contraction degree is less than the solar elevation angle on the local winter solstice.

The result of the computer simulation reveals that the contraction degree of the Observatory makes it possible that there will be no shadow at noon during a long period, and the period has no correspondence with the key dates of calendar and astronomy. Considering the building has been keeping the original form until now, though legends about it have been popular among people, the precise analyzing result is objective and indicates that the Observatory is not mysterious.

Here comes another question: why was the Observatory built into such an irregular platform if not out of the purpose of ancient designers?

We note that the bricks in the exterior of the Observatory have such characteristics:

a. The 3D model reveals that every side of the Observatory is an irregular hyperboloid because of the different plans of its bottom and top;

b. The brick joints on the south side are straight while those on the northern, eastern and western sides of the Observatory are askew. The geophysical exploration shows no asymmetrical subsidence of the building foundations, which means that the askew brick joints were made by ancient craftsmen on purpose;

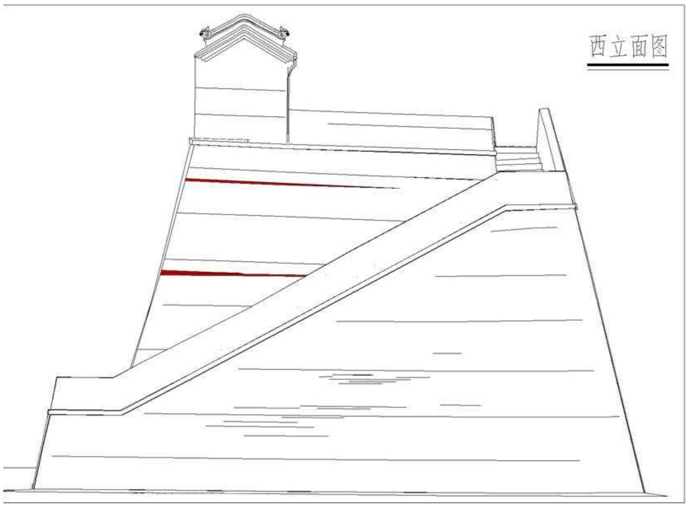

Figure 4: Askew bricks-laying on western facade

c. There are two holes on the eastern wall, which were caused by the Japanese army's bombardment during World War Ⅱ and kept to show the history during the restoration in 1975. We can see the exquisite techniques of ancient craftsmen through the parts on the rim of the holes: the exterior of the bricks were specially made askew, and each brick was laid with the higher part outside and the lower part inside. The two methods were combined, and formed the design of the Observatory featuring obvious large lower part and small upper part.

Through simulation of the brick-laying process on the computer according to the above information, we find that on the premise of the askew exterior of the brick, the askew laying of the brick and the askew brick joints, the platform naturally became higher in north and middle while lower in south, east and west as the bricks were laid layer by layer from bottom to top. Each side became an irregular hyperboloid, which is the same as the real design of the Observatory.

That is to say, the peculiar design of the Observatory was an accidental result of the construction methods adopted by ancient craftsmen.

Of course we still have some questions remaining unresolved. For example, why did the designer or craftsmen pursue the design of askew top for drainage won't need such a steep gradient (the current gradient reaching 3%)? From available materials at present, this has no relationship with astronomical needs.

4.2 Restore the construction order of ancient craftsmen

Was the whole Observatory made of bricks or was it made of rammed earth inside and enclosed by bricks outside? Were the central platform and the steps built from the bottom to the top at the same time, or was the central platform built first before it was enclosed by a flight of steps? These relate to not only the restoration of the construction process of ancient craftsmen, but also the degree of potential risks of the Observatory. We have made initial conclusion via the result of geophysical exploration.

As for the central platform, thick layers of different strata have been found on three locations: 0.25m, 0.5m and 0.75m deep from the surface to the interior, while no obvious reflecting layer further inside. This indicates that the centre of the platform was made of an even medium, which is possibly the rammed earth by sampling. There are three layers of bricks on the exterior. From the eastern hole we can see the first two layers of broken bricks and the third layer of well-preserved bricks.

For the side wall of the steps, there are also three layers of bricks on the surface and rammed earth inside. There is a reflecting layer 1.7m further inside, and even medium further. The depth completely corresponds to the width of the steps. This proves that the rammed earth of the central platform and the steps were made at different times.

To build the central platform with rammed earth first, then enclose it with a layer of steps with rammed earth, and finally enclose it with three layers of bricks. This is the simplest and cost-saving of all construction methods, and was the final selection of ancient craftsmen.

4.3 Brick processing techniques and age-dating

There is another detail which was not noticed during the period of visual study but revealed thoroughly when the brick joints were traced with the total station system: the brick joints on each layer of the exterior of the central platform was made askew, moreover, one layer of wedge bricks was laid every several layers. We have found two layers in the north, and three layers in the east. This further indicates that ancient craftsmen pursued the askew design on purpose, and proposes a new question: what's the age of the bricks?

The brick processing techniques in ancient China are greatly different from those in modern times. Ancient craftsmen would not directly use the brick. Instead, he would grind off about 5mm of the surface by chopper or grinder, or make the surface of the brick into various peculiar shapes before use them for the architecture. Till today, craftsmen who master traditional architectural techniques follow the method, which was believed to originate from the early Ming Dynasty, or the mid-14th century.

For the Observatory of the Yuan Dynasty, the bricks have askew surface, moreover, there are a lot of peculiar wedge bricks. While marveling at the exquisite techniques of ancient craftsmen, we doubt the age of the material.

We answer this question by thermoluminescence technology.

Restricted by the principle of causing no damage to the building, we have collected limited samples. Fortunately, the test result provides us with powerful evidence: one sample dates back to the 16th century, and the other to the 13th ~ 14th century. The former corresponds to the repair in the Ming Dynasty which was recorded in historic books, and the latter corresponds to the construction time of the Observatory.

This indicates that the Observatory in the Yuan Dynasty adopted the form of bricks on the exterior, and only some of the bricks were replaced during the renovation of the Ming Dynasty. Although we can't prove that the five layers of wedge bricks originated from the Yuan Dynasty, the askew design revealed that brick processing techniques had appeared in the Yuan Dynasty, changing one of our views on the history of ancient Chinese architecture.

4.4 Asymmetrical subsidence

To explore the foundations, surface wave prospecting and refraction survey are adopted. The former has seven observation lines, two in the east of the Observatory, one in the south, one in the north, and three in the west. The latter has two such lines, one in the east and the other in the west of the platform.

In the profile of the speed of surface wave, the movement of the speed distributes layer by layer, basically parallel with the formline. This is the same to the longitudinal wave speed. The results of the two prospecting methods agree with each other. Both regularly change, distribute layer by layer, without any part of sudden change. Judging from this, in the surrounding areas of the foundations of the Observatory, no unfavorable geological condition such as cavity and water sac exists.

The bearing capacity of the foundations is far larger than the vertical stress of the Observatory (125kPa) measured by N63.5, therefore, its stability under the influence of gravity is secured.

Various test results available so far can't prove the idea of asymmetrical subsidence.

4.5 How serious are the cracks?

The cracks on the exterior of the Observatory startle us and make us doubt its stability. The geophysical exploration result is optimistic: these cracks are largely distribute on the three layers of bricks on the exterior, and haven't penetrated into the deep platform.

The profile of radar scanning reveals that the Observatory has five large cracks in the northern side, four in the western side, seven in the southern side, and nine in the eastern side. All of them distribute in the parts less than 0.75m deep, some penetrating into three layers of bricks, some only into the first or second layer, and some broken between the second and the third layers. The part of rammed earth more than 0.75m deep has no cracks.

Overlapping the scanning result of the interior and the distribution map of brick cracks (no matter long or short) on the exterior, we find that there is no direct correspondence relationship between the inner and outer brick cracks. That is to say, the inner and outer brick cracks were resulted from local stress, and they can't reflect more problems.

5. Conclusion

When the Observatory is mentioned at first, the problems we face seem complex: its historic information is somewhat related to legends, and its preservation state is terrifying.

However, accurate measurement and scientific test lift the veil surrounding the Observatory. They involve diversified and multi- disciplinary techniques, making the organization and preparation of the result report a little confused (for example, it's hard for me to integrate various researches in a unified language in the 3rd and 4th parts of the paper). They also mutually promote and influence each other in comprehensive analysis. For example, the brick processing techniques, the brick age test and the foundation scanning shall not be independently analyzed, but need overall research.

The final result is inspiring. Accurate measurement and scientific test help us understand more about the true history of the Observatory, and provide heritage conservation engineers with more information during the design process, avoiding improper measures.

Many other efforts have been made during the whole conservation and design process, such as monitoring the environment, testing the dirt on the exterior of the bricks, carrying out pathological analysis, and assessing the structural stability. They don't relate much to the theme of the paper, and I will not talk more about them.