RESEARCH ON NON-DESTRUCTIVE TESTING TECHNOLOGY IN CONSERVATION REPAIR PROJECT OF ANCESTRAL TEMPLE IN MUKDEN PALACE[1]

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ABSTRACT:

Due to the use of wood and other non-permanent materials, traditional Chinese architecture is one of the most fragile constructions in various heritage objects today. With the increasing emphasis on the protection of cultural relics, the repair project of wooden structure has become more and more important. There are various kinds of destructions, which pose a hidden danger to the overall safety of the ancient buildings, caused not only by time and nature, but also by improper repairs in history or nowadays. Today, the use of digital technology is a basic requirement in the conservation of cultural heritage. Detection technology, especially non-destructive testing technology, could provide more accurate records in capturing detailed physical characteristics of structures such as geometric deformation and invisible damage, as well as prevent a man-made destruction in the process of repair project. This paper aims to interpret with a typical example, Ancestral Temple in Mukden Palace, along with a discussion of how to use the non-destructive testing technology with ground penetrating radar, stress wave, resistograph and so on, in addition to find an appropriate protection method in repair project of traditional Chinese wooden architecture.

1. Introduction

With the increasing emphasis on the conservation of cultural relics, the restoration work of historic buildings has become more and more important. Basically, most of the ancient buildings in China are wooden structure. Wood is a flexible material which could resist deformation in the earthquake. The drawback, however, is that they are susceptible to temperature, humidity and other external influences (which will lead to rot, cracks, tilt, foundation settlement, etc.), and poses a hidden danger to the entire architecture. Besides, after years of use, the decline in mechanical properties could affects their bearing capacity. Moreover, traditional testing technology and restoration methods, determining restoration and demolition in the absence of accurate and effective detection and evaluation methods, like samping, eyeballing, knocking, which are simple and depend largely on manual experience and lack accuracy, will cause the loss of historical information of ancient construction, and even cause a certain degree of damage to wooden structure.

Today, digital technology, especially non-destructive testing technology, could provide accurate records in capturing detailed physical characteristics of structures, such as geometric deformation and invisible damage, will prevent secondary man-made destruction in the repair process.

This paper, in the form of case study of Ancestral Temple in Mukden Palace, aims to introduce non-destructive testing technology (ground penetrating radar, stress wave, resistograph and so on) and explore an appropriate protection method in the repair project of traditional Chinese wooden architecture.

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2. Project Overview

2.1 Mukden Palace

Figure 1.The aerial view of Mukden Palace

Early construction of Mukden Palace began in 1625 by Nurhaci, the founder of the Qing dynasty. In 1631, additional structures were added during the reign of Huangtaiji, Nurhaci's successor. The Mukden Palace was built to imitate Beijing's Forbidden City. However, the palace also shows the cultural characteristics of Manchu and Tibetan (Figure 1)[6].

In 1780, the Qianlong Emperor further expanded the palace. Every year since then, successive Qing emperors usually stayed at Mukden Palace for some time.

2.2 Ancestral Temple in Mukden Palace

Ancestral Temple, located on the east side of the Great Qing Gate of Mukden Palace, is an antique-courtyard-style building (Figure 1). The temple is off the beaten track as it doesn't belong to the main part of the palace.

Ancestral Temple was built on an independent two-meters high platform, and formed a typical enclosed courtyard (四合院). This building complex consists of six buildings: main hall (Figure 2), temple gate (Figure 3), two side halls with one penthouse each (Figure 4). The main hall is an extends five(五间) building with front porch and Xieshan(歇山) roof covered with yellow glazed tiles. To the southwest of the main hall, located the Fen Jin pavilion (焚帛楼), which was used for sacrifice. To the east and west of the main hall, there are two side hall, which are extends three(三间), Yingshan(硬山) roof with yellow glazed tile. There is a penthouse in the south of each side hall. On the south of the

Figure 2 The main hall of Ancestral Temple in Mukden Palace

Figure 3 The temple gate of Ancestral Temple in Mukden Palace

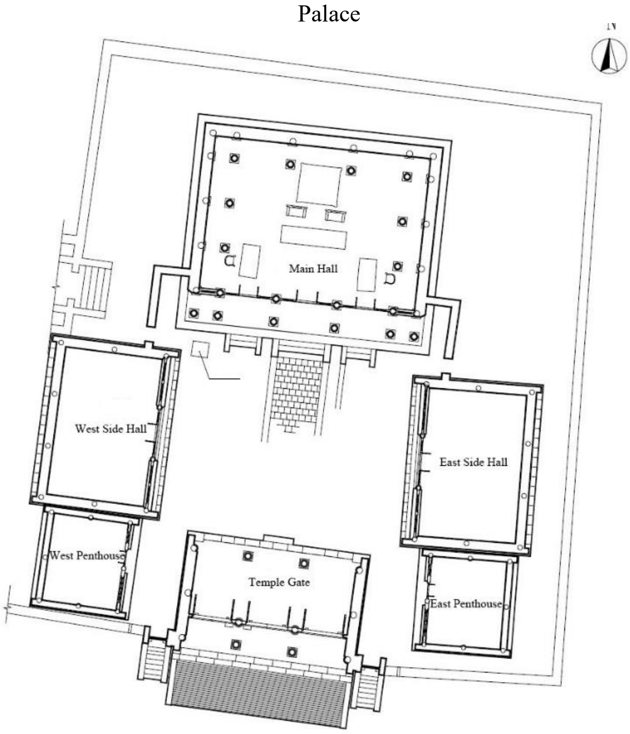

Figure 4 The general layout of Ancestral Temple in Mukden Palace

courtyard is the temple gate, extends three, depths two, yellow glazed tile roof, Hard Peak.

The palace in the Imperial Ancestral Temple set wood and brick as its main building materials and set timber frame as the main structure pattern. Such a structure pattern is composed of stand column, beam and girder; each nodal point between the components fits with the mortise and tenon joint, which from a flexible framework. There is a clear division of the responsibility between load bearing and building envelope, among which the weight of roof is borne by wooden frame. That structure, because of the false wall, gives the building great flexibility. What's more, the structure, to a certain extent, also reduces the damages caused by the earthquake.

3. Non-destructive testing technology

As a new digital technology, non-destructive testing technology plays an important role for the ancient building conservation. Non-destructive testing is the adoption of physical mechanics or chemical properties to effectively test and inspect the relevant characteristics of the target object (such as shape, displacement, stress, optical properties, fluid properties, mechanics, etc.) without destroying the structure and operational performance of the detection target[3].

With the research and development of new digital technology, non-destructive testing technology has integrated GPR, stress wave and resistograph to overcome the shortcomings of single testing technique and increase the accuracy of the test results. Comprehensive comparison and data analysis would improve the accuracy of the location and condition of the damaged parts, and make it possible to explore a new way to repair damaged wooden structure.

Non-destructive testing technologies have overcome the shortcomings of the traditional detection method, and can be used to visually assess the condition, even internal, of timber structure. Several common non-destructive testing technologies are applied in the research of Ancestral Temple in Mukden Palace.

3.1 Ground penetrating radar

GPR is a fast and efficient, high-precision non-destructive testing technology. In the beginning, radar detection technology was mainly used for underground exploration, while later, with the development of high-frequency electronic technology and computer data processing technology, GPR was also used in expanding fields.

Figure 5 Ground penetrating radar

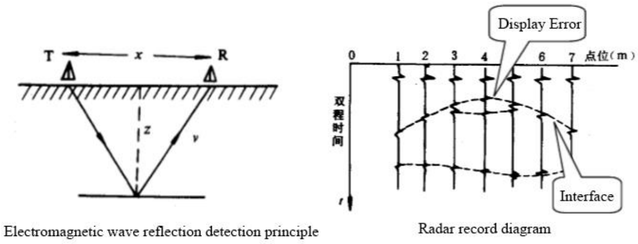

Figure 6 Working principle and recording diagram of GPR

GPR is a method of using radio waves at the frequency of 106-109Hz to determine underground media distribution. It is mainly composed of integrated frames, antenna and related accessories (Figure 5). GPR detects target by emitting high-frequency broadband short-pulse electromagnetic waves to the ground or target body through the transmitting antenna. The waves are then reflected by subsurface stratigraphy or target body, and received by the receiving antenna. The path, field strength and waveform of electromagnetic wave, while propagating in the media, will change with the changes of the dielectric and geometric properties of the media (Figure 6)[4]. As the difference in the dielectric constant of air and soil is significant, GPR will get intense reflected signals when the target body has obvious gaps or holes. As shown in the figure 7、8, from the south side of the main hall of the east gable, there is a void phenomenon below 200mm-650mm of the foundation at 10m of the wall.

The test result of GPR in ancient architecture is more accurate and feasible, providing a strong support for the protection and reinforcement of ancient architectures. However, it also has some

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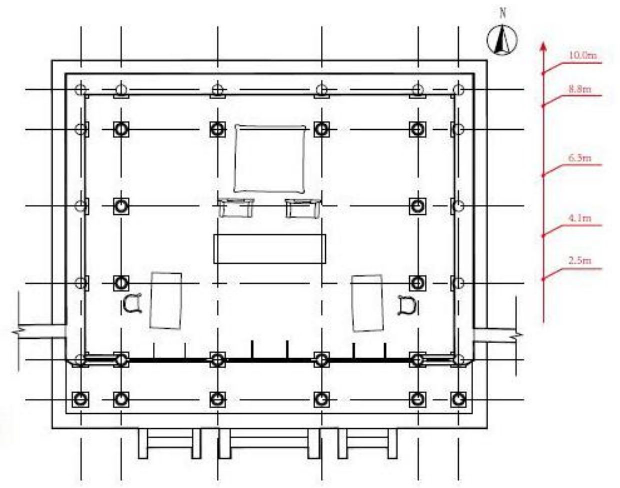

Figure 7 Plan sketch of the main hall

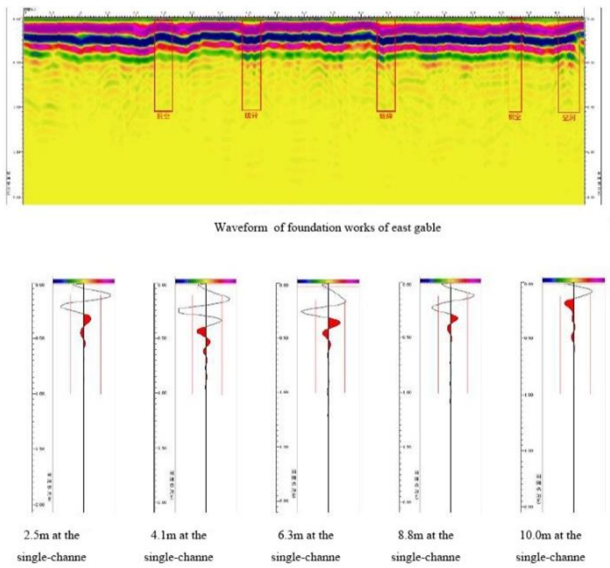

Figure 8 GPR analysis of the main hall of the east gable

limitations, with the increase of detection depth, the detection accuracy is reduced, further affecting the detection quality.

3.2 Stress wave

Stress wave technology, detecting wave velocity and vibrational spectrum through sensors, is one of the most common methods of non-destructive testing of wood and wood-based composites[7]. Depending on the actual diameter of the detected object, we can arrange 6, 8, 10 or even more sensors around the detection section (Figure 9). The shorter the diameter is, the fewer sensors are needed. And the more sensors, the more accurate the test value will be. The height of the detection section was determined by the height, the appearance damage and the surrounding environment of the wooden structure. Researches have shown that stress wave of healthy wood propagates in a certain range of

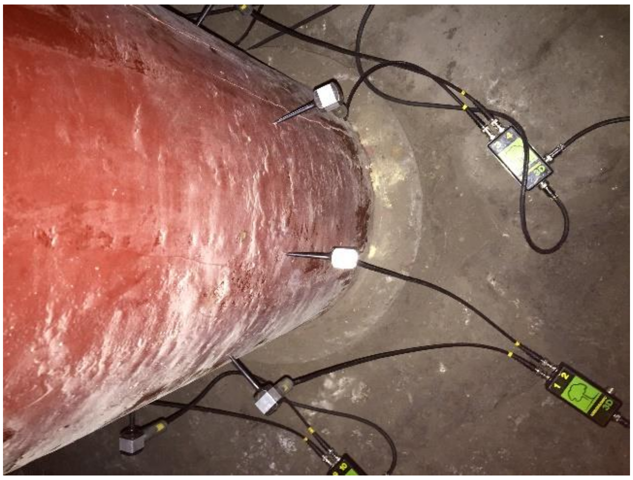

Figure 9 stress wave probes in operation

velocity. If the wood is decayed or worm-eaten, the propagation velocity would decrease sharply. Where wave speed is lower than the speed of healthy wood, the part can be judged as decayed or worm-eaten. According to the propagation speed of the internal structure of the wood, defects and damage can be encoded on pseudo color image, where unhealthy parts are indicated by red and blue, and healthy parts by green and yellow.

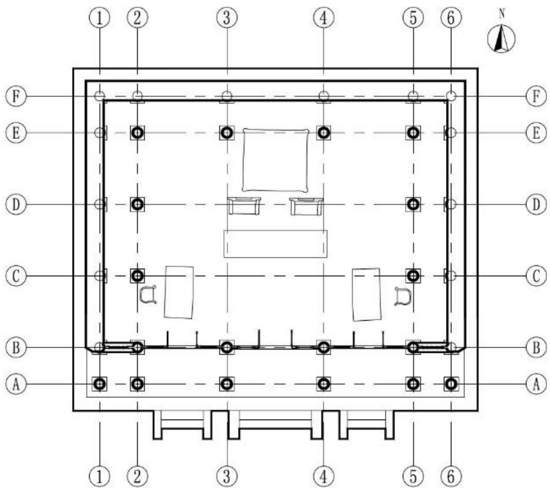

Figure 10 Plan sketch of the main hall

First, measure the circumference of the target structure. In the main hall, the circumference of D5 pillar at the height of 20cm (Figure 10) was about 320mm. The perimeter was evenly divided into 10 parts by 10 sensors (FAKOPP) which could detect stress wave. Knock each sensor 3 times with a small hammer, and the average propagation time was taken as the propagation time of the measurement sensor point. By combining the distance and propagation time between the measured points, the stress wave propagation velocity could be calculated, which were later process pseudo color image (Figure 11). As the image shows, the red part is in damage, in which the average value of the velocity of propagation is 709m / s and 818m / s, which is lower than the lowest average of health. The cracked area accounts for 14% of the total.

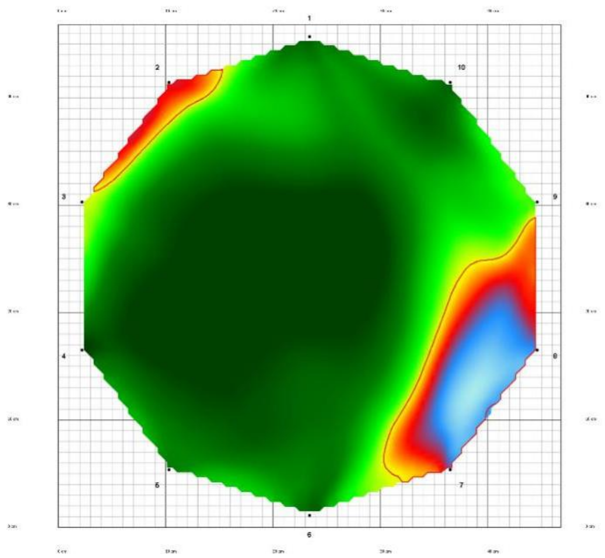

Figure 11 Stress wave pseudo image of D5 pillar of the main hall

3.3 Resistograph

Figure 12 Resistograph

The wood resistograph mainly composed of probe (and its protection device), the microcomputer system and the storage battery (Figure 12). To detect damages, the micro-probe, 1.5mm in diameter, driven by motor, was stabbed into the interior of wood at a uniform rate. The computer records what the resistance pressure is for this process into the memory card, and print the output test photos, which were processed into two-dimensional graphics to indicate internal defects in the pillars section [2](Figure 13). The resistograph maps decayed degrees and wood age through different resistance values, and form curve image. Moreover, with the help of stress wave detection, which could find out the most damaged area with the probes radially stabbed in, the damaged condition of wooden structure would be determined more accurately through the data comparison between the resistograph and stress wave.

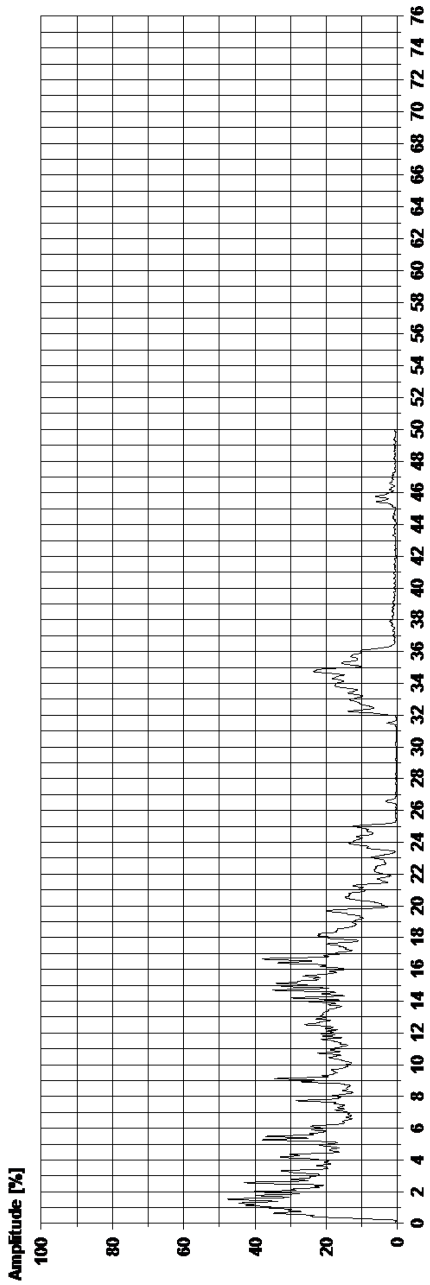

Figure 13 Resistograph two-dimensional chart of D5 pillar of the main hall

4. Testing results of Imperial Palace in Shenyang

After external observation, the use of ground penetrating radar, stress wave and resistograph, the data was sorted and analyzed to obtain the detection result. The main damages of Ancestral Temple in Mukden Palace are as follows:

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4.1 Cracks

Figure 14 Wooden structure cracks of the temple gate

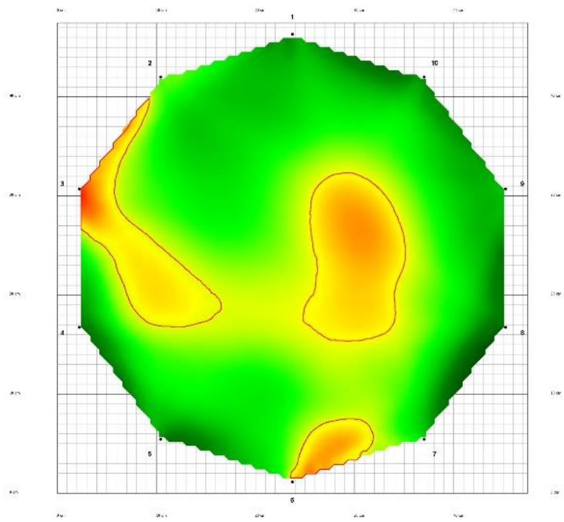
Figure 15 pillar cracks of the temple gate

Figure 16 wall cracks of the temple gate in the west

There are two kinds of cracks: entire crack and partial crack. The cracks of the temple were mainly in walls, beams, pillars, eave-rafters, etc. (Figure 14、15). For example, there are cracks in the east and west gable of the temple gate, which are about 20mm wide at the top and 10mm wide at the bottom (Figure 16). 80% pillars in the main hall have cracks, such as part of Liang Fang, boarded door, and eave-rafters. There are two main reason for the cracks. One is that the structures have been worn down by the years and fallen into disrepair. Long-time load has weakened the bearing capacity of beams and pillars and leads to cracking. The other reason is that the moisture erosion has caused different swelling or shrinkage inside and outside the wood fibers, which lead to the structure cracking.

4.2 Decayed

Years of humid environment and rain corrosion (result from unmaintained leaking roof) accelerated the deterioration of ancient wooden structures. The main hall, the temple gate, two side halls and two penthouses decayed in varying degrees. For example, the D2 pillar of the main hall, by comparing and analyzing the data of the stress wave (Figure 17) and the resistograph (Figure 18), was mild decayed in the inside and partly cracked in the outside.



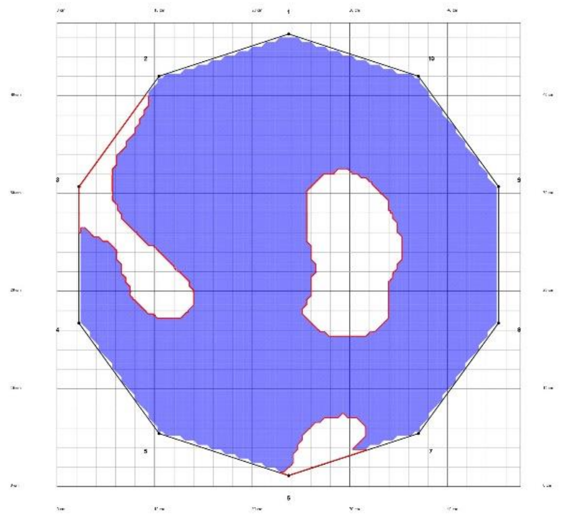


Figure 17 Stress wave pseudo image of D2 pillar of the main hall

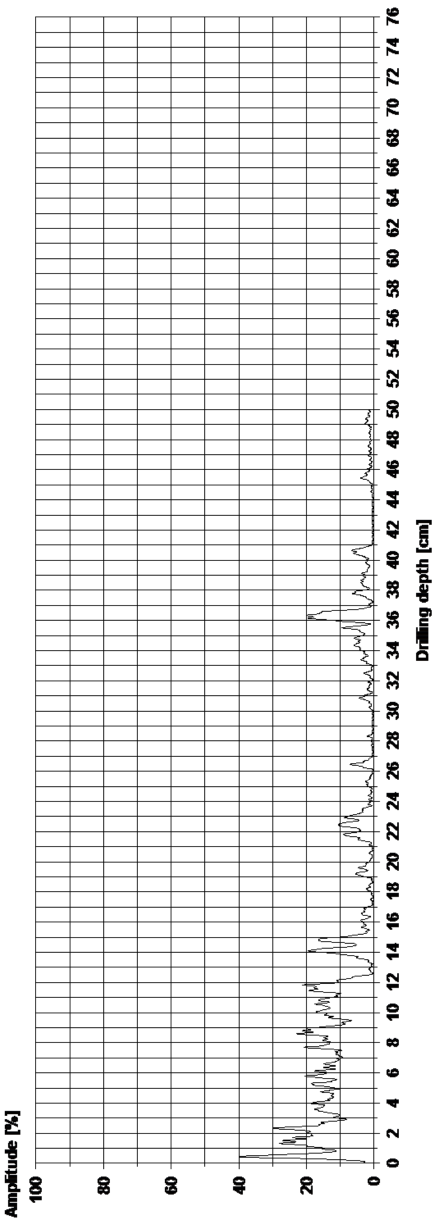


Figure 18 Resistograph two-dimensional plane detection chart of D5 pillar of the main hall

Figure 19 Settlement of the pedestal of the temple gate

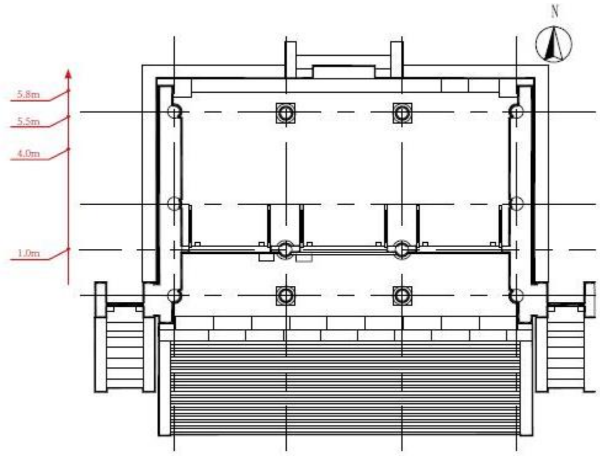


Figure 20 Plan sketch of the temple gate

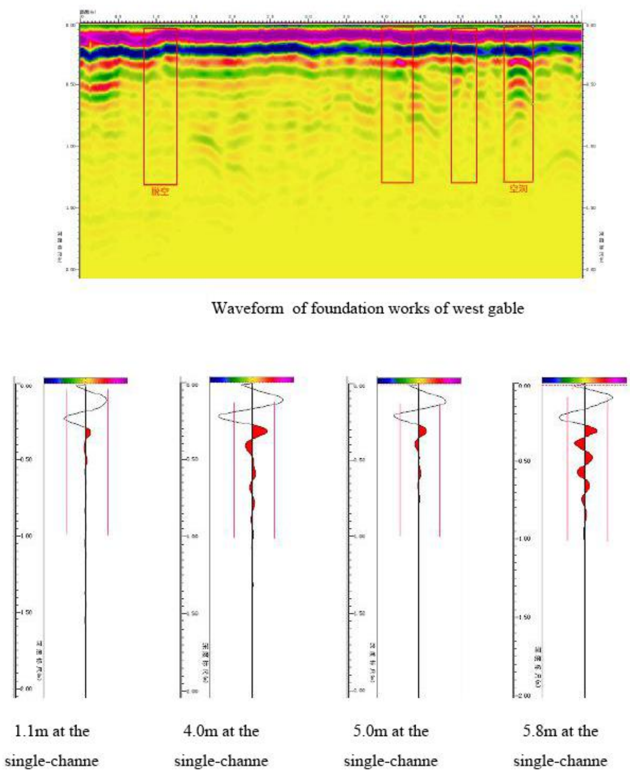


Figure 21 GPR detection analysis of the temple gate of the west gable

4.3 **Settlement**

Uneven settlement of the foundation would cause the tilt and decline of the walls and wooden structure. In Ancestral Temple in Mukden Palace, the most obvious settlement happened around the temple gate (Figure 19). Through the application of the GPR, we found that the uneven settlement (Figure 20、21) of the pedestal in the northwest corner of the temple gate leaded to the cracks in the wall and serious decline in the wooden structure (Figure22), threatening the stability and safety of the entire building.

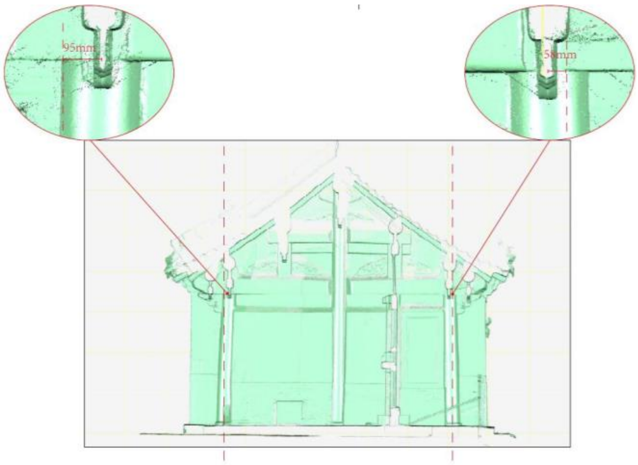


Figure 22. Decline of the wooden structure of the temple gate

5. Conclusion

After hundreds of years of erosion, there were different degrees of damage, decline and other damages happened in Ancestral Temple in Mukden Palace. Basing on the traditional detection methods, the use of advanced GPR, stress wave and resistograph is conducive to assessment inside conditions of wooden structure, and could provide a reliable basis for the follow-up restoration work. Having avoid the weaknesses of solely relying on experience and surface estimate, the restoration plan would be developed in a better way. Although there are some errors between diagnostic results and actual damage conditions, and some minor damage to the wood frame which only occurs in original intonaco of the pillars, without affecting the structure and use of the main body. In general, non-destructive testing technology will provide a promising way to make the restoration of ancient buildings more scientific.

Based on the present situation of Ancestral Temple in Mukden Palace, this paper analyzed the important role of digital technology in the restoration and informatization work of the ruins. Non-destructive testing technology, by changing the traditional repair and protection from the macroscopic visual way into scientific quantitative analysis, provides reliable data support for the fixation and restoration of the wooden beams, columns, corbels and brackets. Comprehensive use of various non-destructive testing methods can complementarily improve the detection accuracy, and effectively enhance the level of ancient buildings protection.

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