Study on inverse calculation of load based on settlement of wooden pillar at Tianluoshan site

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ABSTRACT

Wooden architecture sites are important archaeological objects in southern China. Existing archaeological studies generally believe that the settlement architecture of the Hemudu period is single-story pile-dwelling. Because of its unique geological conditions, a large number of well-preserved wooden pillars have been unearthed in the Tianluoshan site, Zhejiang province, China. Based on the huge settlement founded under wooden pillars at this site, the historical load on the wooden pillar was calculated in reverse according to the calculation method of foundation settlement. Then the tribal architectural form at that time can be inferred according to the layout map of the wooden pillar at the Tianluoshan site. The results show that the Hemudu culture could build multistory buildings already, which presumed to be sacrificial buildings.

Keywords: Tianluoshan site, wooden pillar, inverse calculation, creep, foundation settlement

1 INTRODUCTION

Hemudu Site, which has been more than 6500 years since then, is located in the middle and lower reaches of the Yangtze River. It has exerted extensive and far-reaching influence on many disciplines and research directions. At the same time, there are still some problems to be solved urgently in the aspects of cultural origin, rice planting, wooden pile-dwellings, and settlement morphology. The discovery of Tianluoshan site provides us with an opportunity to re-contact the Hemudu culture (Sun, 2004). According to the drilling results, the Tianluoshan site in Zhejiang province, China, covers an area of more than 30000 square meters, and there is a complete ancient village about 6000 years ago buried 2~3 meters underground (Fig. 1).

Wood is inherently perishable and few sites have been unearthed with well-preserved wood. However, a large number of well-preserved wood components had been unearthed at the Tianluoshan site due to its unique geographical conditions of low altitude, high water level and dense soil. All these conditions have helped wood basically isolate from the air, which slowed down the degree of wood oxidation. Most of pillars found in Tianluoshan site have a section size of 40 cm × 40 cm, with the largest up to 50 cm × 50 cm, which is very rare in archaeological discoveries (Fig. 2). In the process of further excavation, the archaeologists found that these wooden pillars had produced a huge settlement in the process of use. By measuring the excavation profile, the subsidence distance was up to 90 cm. Combined with the calculation method of foundation settlement, the settlement of this part is divided into three parts: instantaneous settlement, consolidation settlement and creep settlement, and then the upper load of wooden pillars can be calculated in reverse according to the pillars’ settlement. Finally, the architectural form of the superstructure at that time is speculated on the basis of measuring plane layout of wooden pillars in the site. This work is inspired by professor Onitsuka’s (2011) research on the Yoshinogari site to study the construction method of a burial mound, and would provide theoretical help for archaeologists to study the architectural structure and livelihood model of primitive tribes.
2 PREPARATION FOR CALCULATION

2.1 Geological condition
Tianluoshan site is located in Ningshao plain, Zhejiang province, China. The site is 30–40 kilometers away from the coastline in the east and about 7 kilometers away from Hemudu site in the southwest (Fig. 3). Based on the analysis of the characteristics of the middle holocene beach rocks and the fauna in the east coast of Zhejiang province (Yang, 1995), and combined with $^{14}$C dating (Jiang, 1996), stable oxygen isotope ratio and other quantitative methods, the climate at that time was warm and humid. The broad coastal continental shelf plain provided sufficient scope for human development at that time. Palaeogeographic studies show that neither the early accumulation layers nor the raw soil layers have been overlaid by the marine sediments, which indicates that the site has never been directly invaded by the sea (Ling, 1992). The site area has not undergone major tectonic movements, and the soil properties tend to be stable (Sun, 2002).

2.2 Investigating of settlement caused by load
The Hemudu people built pile-dwellings to suit the watery environment, and these structures are regarded as a "wonder in the history of architecture". According to the relevant archaeological documents, the construction process of this kind of building form is as follows (Su, 1984):

Firstly, they dug a posthole for pile installation, and then people put the wooden piles into the posthole and filled it with soil. When the wooden piles were stable, they erected various beams on the piles and covered it with boards to form an overhead building base. Finally, people erected pillars and beams on the boards to form a "pile-dwellings" house higher than the ground.

During the excavations in Tianluoshan site, the archaeologists found that most of the wooden pillars could be clearly seen from the section that the bottom of the wooden pillars broke through the bottom of the posthole (Fig. 4). Considering the architectural form of the Hemudu period (Mou, 1979), we can assume that the distance of the breakdown part is the settlement value generated during the use of the wooden pillars.

3 CALCULATION AND ANALYSIS

3.1 Model simplification
According to the engineering geological exploration data provided by the archeologists in Tianluoshan and the borehole histogram, static penetration curve and engineering geological section obtained by the method of drilling core, the soil layer of Tianluoshan site is simplified into a five-layer model of "miscellaneous soil - clay - peat soil - soft soil - silty soil" with a total thickness of 13 m (Fig. 6). The geotechnical properties
of each layer are shown in Table 1.

The depth of postholes in Tianluoshan site is about 1.5 m. In combination with the construction method of pile-dwellings mentioned above, this paper idealizes the wooden pillar into friction pile, and the settlement is calculated by using the single pile settlement model of friction pile (Zhang, 1992). The model considers that the pile sinks together with the soil around the pile under the action of pressure $P$, and finally forms a foundation pressure circle at the plane of the pile tip. Then the settlement of the soil caused by pressure $P$ acting on the pressure circle can be considered as the settlement of the pile. The settlement of the soil under the pressure circle is calculated by the layerwise summation method.

The simplified calculation model is shown in Fig. 5. Because of the high groundwater level at that time, the clay layer and the soil below can be considered as saturated soil.

### Table 1. Geotechnical properties of soil in Tianluoshan site.

| Soil group          | Bulk unit weight (kN/m$^3$) | Compression modulus (MPa) | Elastic modulus (MPa) | Bearing capacity (kPa) | Cohesion (kPa) | Internal friction angle (°) | Permeability coefficient (m/s) |
|---------------------|-----------------------------|---------------------------|-----------------------|------------------------|----------------|---------------------------|--------------------------------|
| Miscellaneous fill  | 17                          | 1.1                       | 2.5                   | 100                    | 10            | 8                         | 9.00e-6                         |
| Clay                | 18                          | 1.2                       | 5                     | 110                    | 14            | 8                         | 6.00e-8                         |
| Peat soil           | 17                          | 1.1                       | 2.76                  | 60                     | 12            | 15                        | 1.00e-6                         |
| Soft soil           | 18                          | 1.2                       | 2.87                  | 65                     | 8             | 12                        | 1.50e-9                         |
| Silty soil          | 19                          | 2                         | 6.5                   | 110                    | 14            | 28                        | 1.20e-6                         |

Fig. 6. Simplified model diagram of soil layers at Tianluoshan site.

### 3.2 Experiment and calculation

In order to measure the parameters of Tianluoshan clay, the one-dimensional creep experiment was carried out in the laboratory. The experiment was carried out by graded loading, with a total of 7 level of loads. After the first level load is stable, the next level load is loaded, and the deformation measured by timing is less than 0.005 mm/d as the stability standard (Sun, 1999). The load of each level lasts about 6 days, 42 days in total. The test was divided into two control groups, and the results showed that the creep characteristics of the two samples were consistent. In order to save space, only the experimental treatment results of sample 1 are provided below. The whole process creep curve and the strain-time logarithmic curve obtained from the experiment is shown below (Fig. 7 and Fig. 8).

Fig. 5. Diagram of wooden pillar calculation model.

Fig. 7. Creep Curve of the Whole Process.
Fig. 8. Strain-time logarithmic curve of the Tianluoshan clay.

In Fig. 7, it can be seen that Tianluoshan clay has a certain instantaneous deformation at the moment of loading, and then the deformation increases obviously with the time, reflecting the obvious creep characteristics of the soil sample. Moreover, the creep deformation rate gradually decreases with time and eventually tends to zero, which belongs to decay creep. Through the method of determining $t_{c0p}$ proposed by Cassagrande (1940), it can be seen from the Fig. 8 that the area where creep of soil samples began to appear under different loads is concentrated in the 80 min ~ 150 min (shadow area). By calculating the creep settlement value under each load, it is concluded that the creep settlement of the soil sample accounts for about 14% ~ 18% of the total settlement.

According to the definition of the coefficient of secondary consolidation, the coefficient of secondary consolidation under different pressures is obtained from the slope of the straight-line part after the completion of primary consolidation in the logarithmic curve of strain and time under different pressures in Fig. 8. According to this, the relationship between the coefficient of secondary consolidation and the pressure is plotted in Fig. 9. It can be seen from Fig. 9 that the coefficient of secondary consolidation is the largest when the load is about 200 kPa. And when the load is small or large, secondary consolidation coefficient are smaller, and with the increase of load, coefficient of secondary consolidation gradually tends to a constant value. This is because soil particles are gradually compacted as the load increases. The hydration film between the particles shows elastic characteristics, which prevents the particles from approaching each other and reduces the tendency of secondary consolidation deformation. The secondary consolidation coefficient in this experiment finally tends to 0.024.

The settlement of building foundation usually includes instantaneous settlement ($S_0$), consolidation settlement ($S_c$) and creep settlement ($S_s$). In this paper, the settlement is also divided into three parts, Eq. (1). The instantaneous settlement is approximately calculated according to the formula in elastic mechanics, Eq. (2), and the consolidation settlement and creep settlement are calculated by the layerwise summation method, Eq. (3), Eq. (4) (Bjerrum, 1967).

\[ S = S_d + S_c + S_s \]  
\[ S_d = \frac{p b (1-\mu^2)}{E} \]  
\[ S_c = \psi_s \sum_{i=1}^{n} \frac{P}{E_{st}} (z_i \ddot{\alpha}_i - z_{i-1} \ddot{\alpha}_{i-1}) \]  
\[ S_s = \sum_{i=1}^{n} \frac{c_{ai}}{1+e_{oi}} H_i \log \frac{t}{\tau_i} \]

According to the pre calculation, it is found that the load on wooden pillars is far more than 1000 kPa, so the coefficient of secondary consolidation can be taken as 0.026 ~ 0.024 in next calculation. By introducing all parameters into Eq. (4), the creep settlement is calculated to be about 15 cm ~ 20 cm. Then according to the total settlement, the historical pressure on the top of the wooden pillars can be solved according to Eq. (1) ~ Eq. (3), and the result is about 490 kN ~ 550 kN. And when the historical pressure is 490 kN, the instantaneous settlement is about 23 cm, and the consolidation settlement is about 47 cm. When the historical pressure is 550 kN, the instantaneous settlement is about 26 cm, and the consolidation settlement is about 50 cm. The calculated results are close to the actual settlement, so the historical pressure on the top of the wooden pillars can be considered to be between 490 kN and 550 kN.

3.3 Inference of Architectural Formation

At Tianluoshan site, it can be found that these large square wooden pillars are concentrated in the 305-4407 excavation units, with a transverse spacing of about 5 m and a longitudinal spacing of about 6.5 m (Fig. 10). The form of the building unit is not yet complete, but the overall form is likely to be a square wooden structure. Furthermore, according to the analysis of the distribution
trend of timber columns and the spatial layout of the site, it can be concluded that the southeast direction of the excavation area should be the main body of the building, and the location may be close to the central area of the site.

According to the calculated historical pressure on the central column, the pressure on the border column and corner column are converted according to the loading area. Then combined with the orientation map of the wooden pillars measured at Tianluoshan site, the unit area load value of the building at that time can be calculated to be about 14 kN/m² ~ 16 kN/m².

Then according to the calculated load, the building structure is analyzed. If the building was a single-story structure, it must be a storage warehouse, and the columns and beams would bear all the loads of the structure. According to Eq. (5), the maximum bearing load of the beam is calculated. \( \sigma \) is the allowable normal stress of the material. The section size of the beam is 40 cm in height and 20 cm in width according to the wood beam excavated at Tianluoshan site, and it can be calculated that the maximum load of the beam with 6.5 m span is about 10 kN/m. Then the actual load to be borne by the beam is calculated. Because 1/4 of the upper load is directly transmitted from both ends of the beam to the wooden pillars and the load borne by the beam body is about 3/4 of the total load, the actual load to be borne by the beam body is calculated about 22 kN/m ~ 25 kN/m. This results show that the actual load far exceeds the maximum bearing load of the 6.5 m long beam. So the building cannot be a single-story structure.

\[
q = \frac{8W_2\sigma}{l^2} \tag{5}
\]

If the building is a multi-story structure, it can be calculated as follows: The unit load value of wooden structure buildings can be estimated according to the bulk weight of wood and the volume of wood contained in each square meter. The bulk weight of wood is about 720 kg/m³, and according to relevant ancient architectural data, the volume of wood per square meter in palace-style wooden buildings is about 0.5 m³ (Liang, 2012). The calculation results show that the dead load value per square meter is about 3 kN/m². Then considering the possibility that the building may be a sacrificial building at that time, the live load can be 3 kN/m², and the total load of each layer is calculated about 6 kN/m². Then, Eq. (5) is used to check the maximum bearing load of the beam according to the load of each floor. The results show that the actual load to be borne by the beam body is about 9.3 kN/m, so the bearing capacity of the beam can meet the requirements, and the safety factor is about 1.09.

Similar to the calculation of normal stress intensity, the shear stress intensity of the beam is checked by Eq. (6). \( \tau \) is the allowable shear stress of the material. The results show that the actual shear stress of the beam also meets the requirements of the wood shear stress. When the load of each layer is 6 kN/m², the maximum shear stress of the beam section is about 0.5 MPa, which is less than the maximum allowable shear stress of the wood. The safety factor is about 2.6.

\[
\tau_{max} = \frac{3F_{max}}{2bh} \leq [\tau] \tag{6}
\]

Based on the above calculation and analysis, it can be concluded that the building is not a single-storey warehouse, but a multi-storey structure. Then, according to the load of the roof, the number of floors of this house is estimated. In Hemudu period, people used branches, thatch and soil to build the roof, and the unit weight of the mixed material is about 1600 kg/m³. Assuming the thickness of the roof is about 15 cm, the load per square meter of the roof is about 2.8 kN/m². The total load calculated by the two-storey house is about 14.8 kN/m², which is close to the load calculated according to the reaction force at the bottom of the pillars. Therefore, this building should be a two-story building (Fig. 11). Considering the scarcity of interior space and people's awe of divine power at that time, this large structure may be a sacrificial building.

![Location map of wooden pillars in Tianluoshan site.](image)

![Building restoration diagram of Tianluoshan site.](image)
At present, it is generally believed that the emergence of the ancient city is closely related to the development of productivity and the emergence of private ownership. It is the product of economic and social development to a certain stage in the process of Chinese prehistoric civilization. The discovery of the ancient city of Liangzhu marks that the period of Liangzhu culture 5000 years ago has entered a mature stage of prehistoric civilization. The discovery of the ancient city of Zhejiang province and the load value of the building is calculated by using existing foundation settlement calculation method. The results show that the pressure on the top of the pillars is about 490 kN ~ 550 kN. Then, according to the location map of wooden pillars at Tianluoshan site, the load value of the building is calculated. Through the stress intensity analysis of the beams and pillars of this building, it is concluded that the building cannot be a traditional single-storey pile-dwelling, which could be a large two-storey sacrificial building located in the middle of the tribal activity area. This proves that Tianluoshan people were able to build multi-storey buildings 6000 years ago.

4 CONCLUSION

In this work, according to the settlement value of wooden pillars found in Tianluoshan site, and combined with the unidirectional compression creep experiment, the historical load on the top of the wooden pillars is calculated by using existing foundation settlement calculation method. The results show that the pressure on the top of the pillars is about 490 kN ~ 550 kN. Then, according to the location map of wooden pillars at Tianluoshan site, the load value of the building is calculated. Through the stress intensity analysis of the beams and pillars of this building, it is concluded that the building cannot be a traditional single-storey pile-dwelling, which could be a large two-storey sacrificial building located in the middle of the tribal activity area. This proves that Tianluoshan people were able to build multi-storey buildings 6000 years ago.

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