Journal of Southeast University (English Edition) Vol. 32, No. 4, pp. 464 – 471 Dec. 2016 ISSN 1003—7985

Stability monitoring and evaluation of the modeled test square for prehistoric earthen sites during excavation period

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Abstract: In order to explore the stability of test square during archaeological excavation for prehistoric earthen sites in Hangzhou, a modeled test square with 2. 3 m in depth, in-plane dimensions of 5 m in width by 5 m in length, and an archaeological column in the middle was excavated by means of a top-down excavation technique. To investigate the stability performance of the modeled test square and the associated effect on the adjacent area, a real-time comprehensive instrumentation program was conducted during the excavation. Field observations included ground settlements, lateral displacement, pore pressure and underground water level. Monitoring data indicates that the ground settlement induced by dewatering and unloading action basically decreases with the increase of the distance away from the pit edge, and the lateral displacements at four sides show a nonlinear variation along the depth. The maximum value is far below the acceptable value regulated by the related standard, which validates the stability of the modeled test square during excavation. Variations of pore pressure and water level suggest that long-term stability should be paid more attention due to the slow consolidation of soft soil. Meanwhile, it is proved that the step shape of the wall can resist lateral displacement more effectively than the vertical shape of wall. This case study provides insights into the real archaeological excavation in Hangzhou, in particular Liangzhu prehistoric earthen sites.

Key words: prehistoric earthen sites; archaeological excavation; test square; stability monitoring
DOI: 10. 3969/j. issn. 1003 – 7985. 2016. 04. 012

As an important type of cultural heritage, prehistoric earthen sites in South China are usually buried underground. Due to the absence of historical documentation, archeological excavation becomes the only way to illustrate the prehistoric life and civilization process[1]. Test square is believed to be an ideal method to obtain archeological information in prehistoric archeology, basically due to the standard profile resulting from the vertical wall surface[2]. Meanwhile, its rectangular shape enables archeologists to read and distinguish the historical stratums and collect relics buried underground without damaging historical information. Due to these advantages, the test square has gained popularity in practice for field archeology. However, during archeological excavation, archeologists pay much attention to archeological information rather than the stability of the test square, and as a result, the collapse of test squares occasionally occurs[3–5]. Failure of the test square not only leads to the disappearance of prehistoric information, but also threatens the safety of archeological and cultural relics. In particular, underground water and soft soil which easily result in the collapse of the test square are constantly encountered during archeological excavations in south China. Therefore, the stability of prehistoric earthen sites during excavation is becoming an urgent issue to be addressed.

The theme of saving historic sites has gained interest and has seen an increasing involvement by geotechnical engineers. It is worth any effort to achieve a convincing explanation for the distress causes and to propose interventions that are safe and respectful to the history of the sites. From a geotechnical engineer's point of view, the test square used in archeological excavation is a typical foundation pit. In terms of the foundation pit, much research on the theory[6–10] and the analysis method[11–14] of stability have been conducted to contribute to the standardization of the foundation pit design and construction. In contrast, the test square has received much less attention. In consideration of archeological requirements, a test square requires vertical profiles, as little intervention during the excavation as possible, keeping cultural relics undisturbed, and long-term exposure to archeological investigation[1]. Current foundation pit engineering almost always involves different kinds of propping measures during the excavation to reduce the exposure time of soil and guarantee safety[15]. It has been discovered that excava-

Received 2016-01-11.
Biography: Chen Wenwu (1966—), male, professor, sungp@lzu.edu.cn.
Foundation items: The National Natural Science Foundation of China (No. 51578272), the National Key Technology R&D Program of China during the Twelfth Five-Year Plan Period (No. 2013BAK08B11).
Citation: Chen Wenwu, Dai Pengfei, Zhang Jingke, et al. Stability monitoring and evaluation of the modeled test square for prehistoric earthen sites during excavation period[J]. Journal of Southeast University (English Edition), 2016, 32(4): 464 – 471. DOI: 10. 3969/j. issn. 1003 – 7985. 2016. 04. 012.

tion behaviors are affected by many factors (e. g., pit geometries, construction methods, soil conditions and retention systems). Hence, different excavation procedures and methods determine different behaviors of the ground pit. In the foundation pit area, many empirical or semiempirical approaches derived from rectangular excavations[16-21] were obtained. Considering that the test square has been widely used in archeological practice, it is necessary to investigate their characteristics and develop relevant stability evaluation approaches for ensuring the safety of archeological and cultural relics and protecting the surrounding cultural information. Due to of the lack of well-documented field data, the characteristics of test squares in south China, particularly those in prehistoric sites, still remain unclear.

To achieve this, well-documented field data is needed, and the archeological excavations of Liangzhu prehistoric sites provide a good opportunity. To avoid damage to true archeological information, a test square under the similar natural and geotechnical background is modeled based on the archeological procedure adopted at Liangzhu prehistoric sites. In order to obtain a better understanding of the behaviors of the modeled test square, ground settlement, pore pressure, underground water table and lateral displacement are measured during the excavation. Finally, the stability evaluation of the modeled test square during the excavation period is assembled to provide valuable information for archeological excavation at Liangzhu sites.

1 Background

1.1 Geographical location

As the concentrated distribution district of Liangzhu prehistoric sites, Hangzhou is located in the lower reaches of Qiantang River in southeast China. Liangzhu prehistoric sites sit on the flat alluvial plain, which features high groundwater tables and thick soft clay in the upper layers.

In view of the invaluable properties of cultural heritage, destructive testing is strictly forbidden on real archeological sites. Therefore, a modeled test square within a similar environment and stratum was adopted to study the deformation and failure behavior during excavation. For this research, the experiment site was chosen at a test base of archaeometry and conservation technology of cultural relics. The site was surrounded by one electrical pipeline in its proximity, open space on the north side, brick walls with 2 m in height on the south and east sides, and the laboratory building (10 m high) on the west side, as shown in Fig. 1.

1.2 Engineering geology and hydrogeology

Prior to excavation, the subsurface conditions and soil properties at the site had been extensively explored by a series of field and laboratory tests. In general, the subsurface conditions feature two layers of fill in the upper 1.15 m below the ground surface, followed by a layer of silty clay (Layer 3) to a depth of 1.50 m. The next layer is mucky clay (Layer 4) extending to a depth of 1.70 m, underlaid by yellow clay (Layer 5) and cinereous clay (Layer 6) until the termination depth of 3.00 m. The observed long-term groundwater table at the site is approximately 0.80 m.

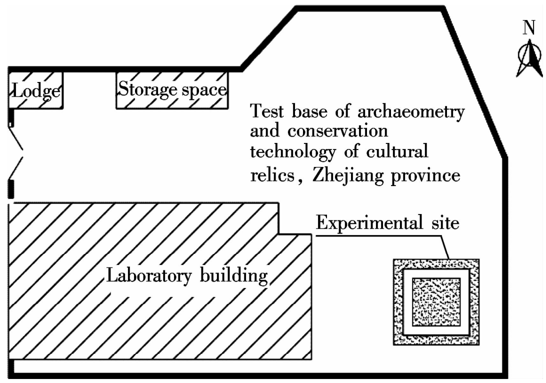

Fig. 1 Plan layout of in-situ experiment

1.3 Excavation procedure

The existence of underground water is extremely negative to the stability of archaeological excavation for prehistoric earthen sites[6,11,14,18,20]. The formation of underground water leads to the decrease of effective stress as a result of the increase of pore-water pressure, which can reduce the shear strength of the soil[22]. Secondly, the formation of underground water can also provide favorable conditions for the original non-saturated soil to absorb enough water and soften, which will also lead to the decrease in shear strength of soil[22]. As a matter of fact, the study area is on the flat alluvial plain, which features high groundwater tables and thick soft clay in the upper layers, as mentioned before, with an extremely humid local environment (the average annual precipitation was 1 100 to 1 600 mm while the average annual evaporation was 800 to 1 000 mm). As a consequence, the excessive groundwater is a negative factor during the excavation process which may not only lead to the destruction of the site but also threaten the safety of archeologists. Hence, some measures need to be carried out to ensure the safety during excavation.

In this paper, two approaches of dewatering methods were applied to ensure the stability of the ground pit: 1) Active dewatering by the pump and 2) Passive dewatering by protective shed. Prior to excavation of the test square, the dewatering trench was excavated around the test square and filled with sand and gravel as well as two pumping wells at the two corners (see Figs. 2(a) to (c)). Meanwhile, the protective shed was built above the test square to protect it from frequent rainfall and facilitate the excavation (see Fig. 2(d)).

After the underground water level was lowered to the depth of 2.0 m, the test square was dug according to the standard procedure of archaeological excavation (the top-down method) as illustrated in Fig. 3. The investigated test square is 5 m in length, 5 m in width, and 2.3 m in depth, with an area in plan of 25 m^2. It consisted of two portions: 1) Archeological column (1.0 m in length × 2.0 m in width × 2.3 m in height) at the center for the presentation of cultural stratum, and 2) A 2.5 m depth of the peripheral rectangular pit, among which south side was one step profile and the others were vertical profiles to make the comparison. The excavation of the test square was only performed at day time and took 5 d to finish in total.

(a) (b) (c) (d)

Fig. 2 Dewatering measurement during excavation. (a) Excavating a trench around the planned test square; (b) Setting two pumping wells at the two corners; (c) Backfilling the trench with sand and gravel; (d) Building a protective shed above the planned test square

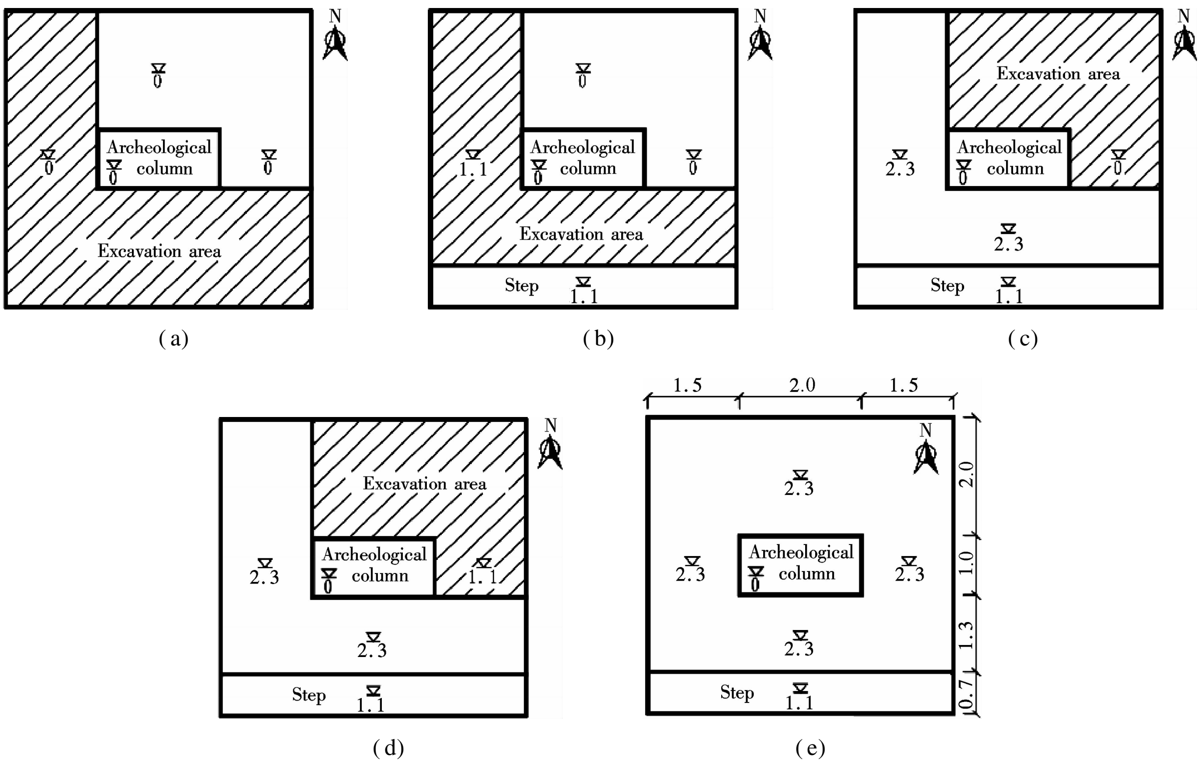

Fig. 3 Excavation procedure (unit: m). (a) The first day; (b) The second day; (c) The third day; (d) The fourth day; (e) The final day

2 Monitoring Plan

To investigate excavation behavior and ensure the safety of labourers, a comprehensive field instrumentation program is conducted during the entire excavation progress, as shown in Fig. 4. Assuming that the modeled archeological column sitting the center of the test square remains stable during the process, the monitoring program excludes the archaeological column. Observation from the entire excavation verifies this assumption.

Although the stability of the modeled test square can be described by a large number of different valuation indices, in this study, emphasis is given to four indices in our paper because they are the most widely accepted and their results can be interpreted in a straightforward fashion. Specifically, the ground settlement and lateral deflection are the most direct indices that reflect the stability of modeled test square. Water level is a factor that indicate the change of surrounding soil condition during the excavation and consolidation period, and pore pressure exhibits the dynamic characteristic change when the ground water goes down. In other literature, some other important evaluation indices are approved for monitoring the stability, such as axial forces and lateral earth pressures[21]. However, the pit retention system is not adopted according to the safeguarding principles for the architectural heritage. Therefore, axial forces and lateral earth pressures are not available in this study.

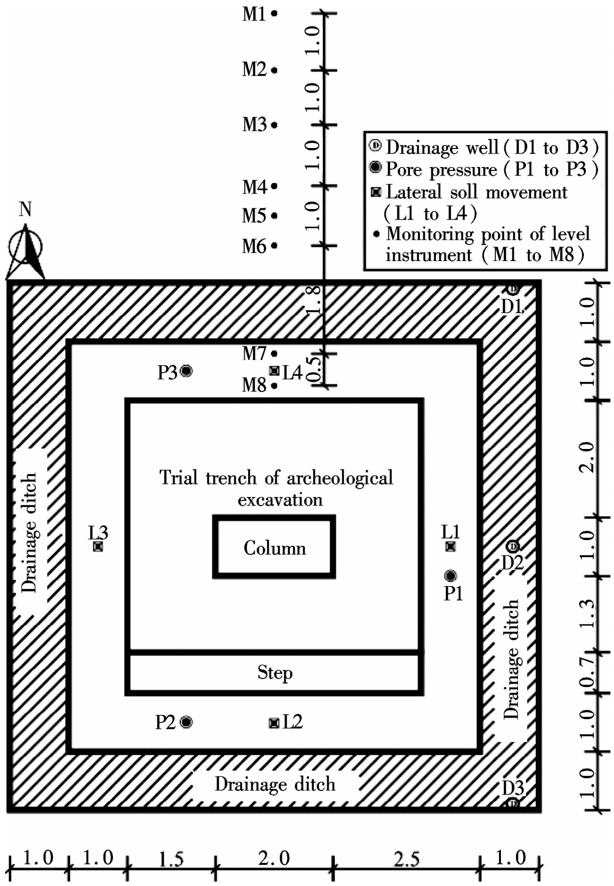

Fig. 4 Monitoring plan layout, plan and cross section (unit: m)

As a matter of fact, the monitored items and related instruments are described as follows. Lateral soil movements are measured by four inclinometer casings (designated as L1 to L4) distributed on each side. Ground settlements are surveyed at one critical section behind the north wall by a level instrument (designated as M1-M8). The positions of level instruments are optimized by the characterization of the ground settlements[14]. The interval between adjacent monitoring points increases with its distance from the foundation pit. Specifically, the interval of M1 to M5 is 0. 5 m (There is a drainage ditch between M2 and M3) and from M5 to M8, the interval is 1. 0 m. The pore pressure at the depth of 1. 5 m is monitored by the vibrating wire piezometer installed inside the boreholes except of west side (designated as P1 to P3) and phreatic water levels are monitored at the observation wells, as described in Fig. 4. The pore-water pressure, slope fissures, deep displacement, actual rainfall intensity and surface runoff were recorded every three hours.

3 Results and Discussion

3.1 Ground settlement

Fig. 5 presents typical ground settlement development over time at Sections M1 to M8. The measured ground settlements increased during the first 47 h; afterwards, it remained stable at a certain level. According to the excavation log, the north wall was finished before 47 h; hence, most of ground settlement which was induced by the unloading of soil mass took place during this period. Meanwhile, some unusual temporary downward ground settlements (for instance, $L = 0.8$ and 2. 64 m) were caused by vibrations from the pumping well in drainage ditch.

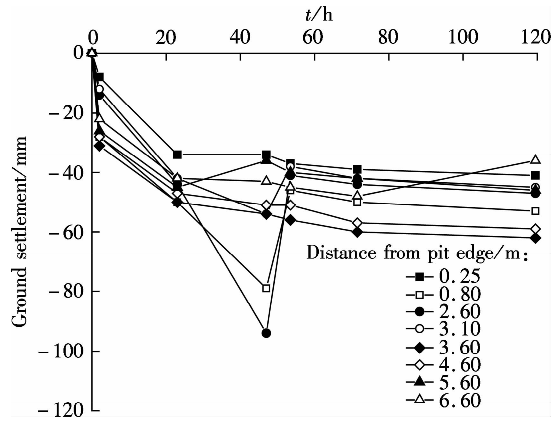

Fig. 5 Time histories of ground settlement at different points

Fig. 6 summarizes the ground settlement distribution along distance from the pit edge. Apparently, there is a small fluctuation along the curve of different excavation time. As normal, settlement distribution has the tendency to linearly decrease from the pit edge with the largest value[21-22]. However, influenced by the embedded drainage ditch ranging from 1. 0 to 2. 0 m, the settlement around the drainage ditch shows a uniform increase except for initial excavation stage (2 h). Meanwhile, transient upward ground movement emerges at the distance from 3. 60 to 5. 60 m. In terms of the amplitude of variation, the largest one arises at the time point (47 h), as a result of overall excavation.

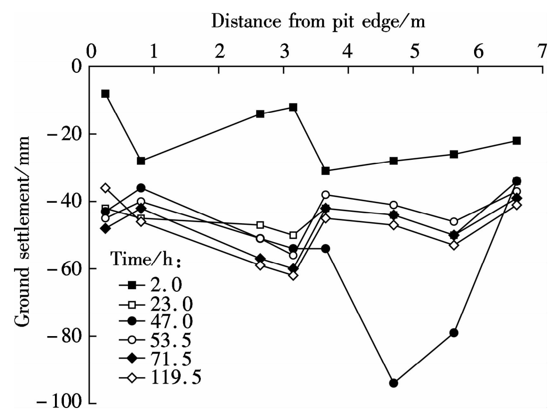

Fig. 6 Ground settlements under different distances from pit edge

Ground settlement was derived from initial dewatering and the following unloading of soil mass induced by modeled archaeological excavation. From the variation curve of ground settlements along the typical section, it is generally concluded that ground settlement decreases with the increase of the distance away from the pit edge without consideration of the effect of drainage trench. As for the scale of ground settlement that occurred during excavation, the value ranging from 3 to 6 cm is far smaller than the acceptable value regulated by the specification (GB 50497—2009), which to some extent proves that the modeled test square maintains stability throughout the entire excavation.

3.2 Lateral displacement

The available lateral soil deflections at L1 at different excavation stages on the east side are shown in Fig. 7(a) and Fig. 8(a). Due to the limitation of monitoring equipment and space conditions, only lateral soil deflection at a depth of 2 m was measured. It can be seen that lateral deflection at monitoring points increases rapidly in the first 23.5 h and then remains stable at a certain level with considerable fluctuations during the excavation process. With the increment of depth, the deflection almost grows linearly. As excavation proceeds, the distribution curve gradually moves towards the left part of the coordinate system, which means that the side wall deforms horizontally backward. Meanwhile, it can be concluded from the distribution curves that the soil continues to nearly deform backward during excavation except the section from 0.5 to 1.0 m after 112 h, and the absolute deflection value is lower than 1.50 mm.

Fig. 7(b) presents the available lateral soil deflections at L2 at different excavation stages on the south side. The analysis is conducted from available data of 2 m in depth. Overall, the time histories of lateral displacement variations show that deflection transmits to a neglective value in the initial period and then increases rapidly into change into a positive value until the peak is attained; afterwards, it remains stable at a certain level. The development process reveals that after initial deformation towards backward, soil horizontal movement runs gradually towards the test square. As can be seen from deflection distribution along depth (see Fig. 8(b)), after the linear growth from top to down in the first day, the deflection curves are characterized by bowl-shaped curves, which typically reveal that deflection increases to the depth of 1.0 and 1.5 m and then decreases at the depth of 2.0 m. With the exception of 23.5 h, the defection distribution moves towards the right side of the coordinate system, which fully indicates that the soil deforms horizontally towards the test square and the maximum deflection occurs at or near the middle part. Similar to the east side wall, the absolute value of the deflection is relatively low (below 2.2 mm), which is actually no threat to the stability of the side wall.

Fig. 7(c) and Fig. 8(c) summarize the lateral soil deflection at L3 at different excavation stages on the west side. In the process of excavation, there is an apparent fluctuation around the zero axis in the initial 75 h, as shown in Fig. 8(c). In other words, soil repeatedly moves backward towards the test square. After that, deflection at all the monitoring points remains stable at a certain level.

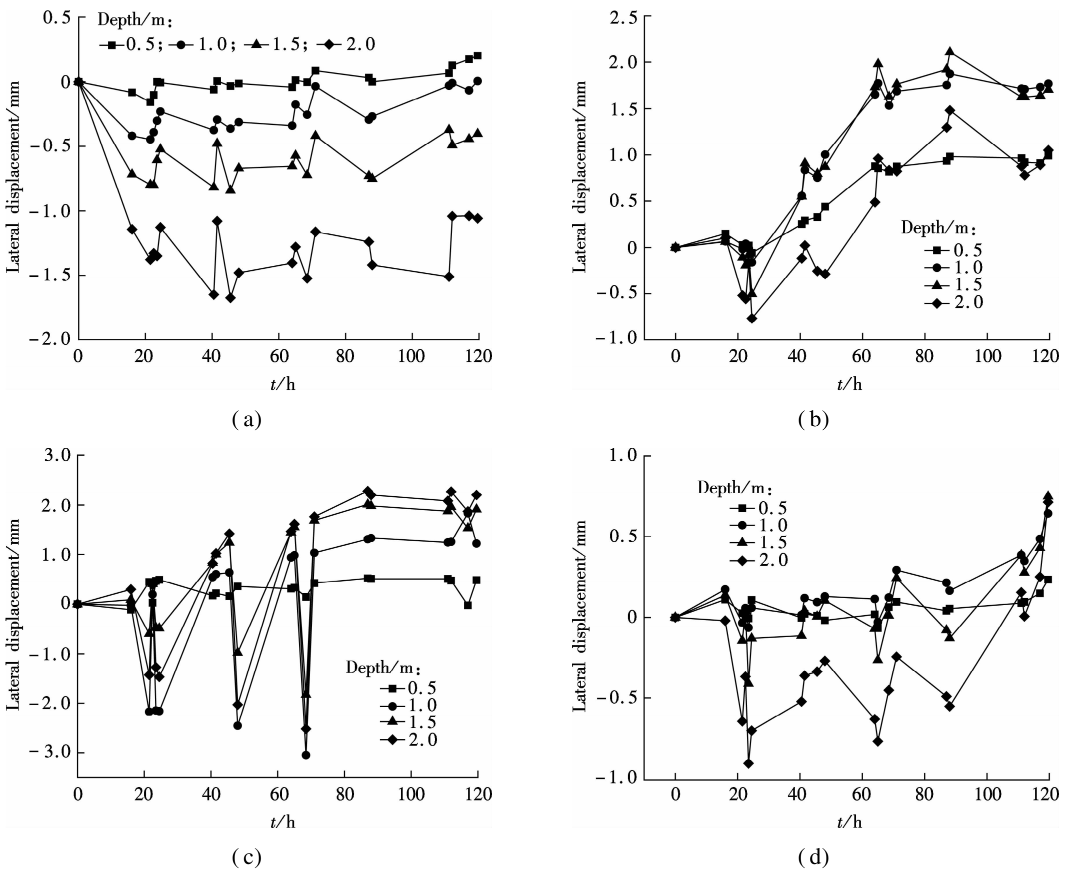

Fig. 7 Time histories of lateral displacement variations. (a) East side; (b) South side; (c) West side; (d) North side

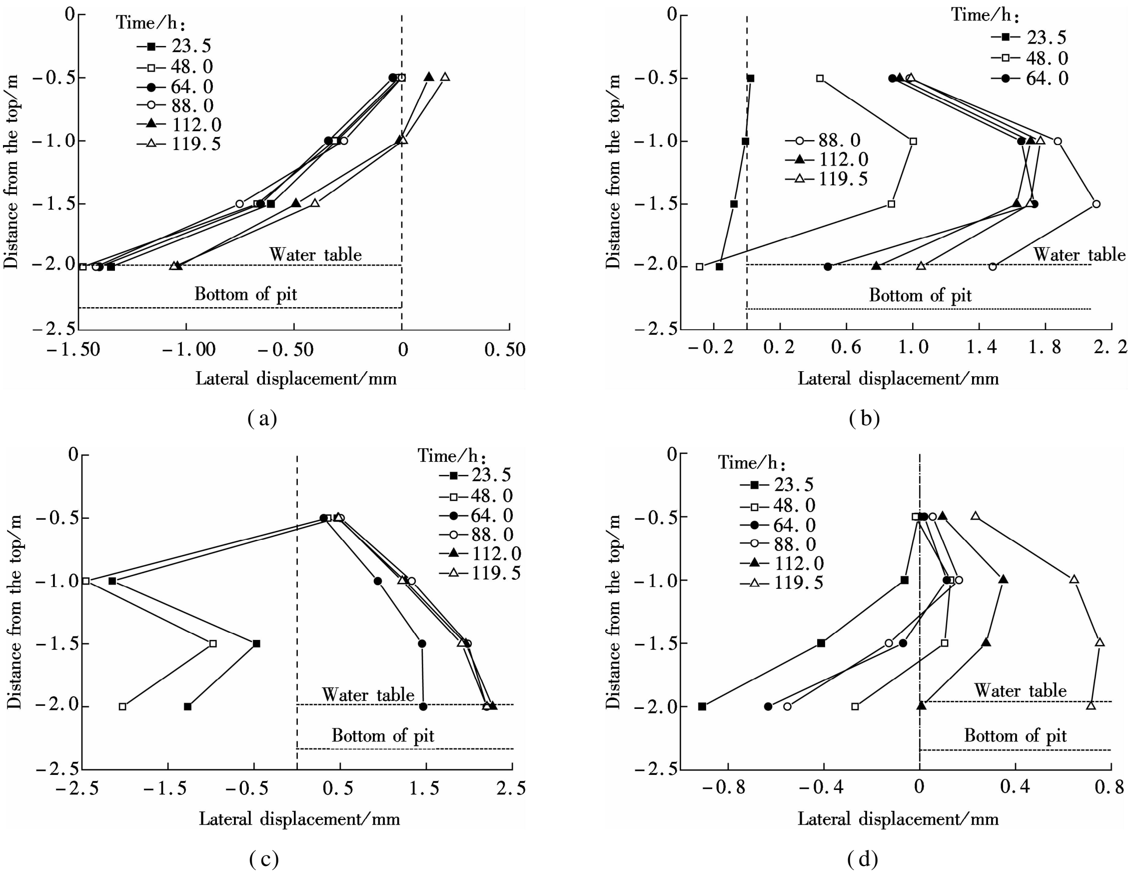

Fig. 8 Lateral displacement at different depth levels. (a) East side; (b) South side; (c) West side; (d) North side

The distribution of deflection along the depth shows a transient irregular variation with a neglect value during the period of the initial 48 h and approximately linear increases with a positive value from top to down, which fully reflect the change of deformation direction. Considering the absolute value of deflection, the maximum value of slant (±2. 5 mm) has no influence on the stability of the side wall.

The available lateral soil deflection at L4 at different excavation stages on the north side is also given in Fig. 7 (d). Except the monitoring point at the depth of 2. 0 m, which has a relative high absolute deflection value during the whole process, the deflection diversely changes around the zero value and finally reaches the peak positive value. By comparison of the distribution curves at different excavation time, as shown in Fig. 8(d), it can be found that curve moves towards the right side of the coordinate system and the shape of curve changes from monotone increasing at 23. 5 h to a bowl-shaped curve after 23. 5 h, and the maximum value occurs at the section from 0. 5 to 1. 0 m. The final results show that the soil moves towards the test square. However, it is no threat to the stability of the pit wall in terms of the maximum value of deflection (−1. 0 and 0. 8 mm).

By comparison of the lateral displacement that occurred on the four sides of the modeled test square, it was found that apparently the distribution along the depth on the east and west sides is different to that on the south and north sides. The distribution curve of the "bowl" shape on the south and north sides has been proved by existing research[8, 19-20]. Meanwhile, the south side with the step shape can more effectively limit the lateral displacement compared to the other three sides with a vertical shape, which is also validated by similar research[23]. However, the phenomenon with initial movement outwards and the following movement inwards occurring on the east and west sides is rarely encountered in past research, which is possibly created by the excavation procedure and occasional shock by excavation and deserves further study. In terms of the maximum lateral displacement, the value below 2. 5 mm is far smaller than the acceptable value regulated by the specification (GB50497—2009), which also proves that the modeled test square is remains stable throughout the entire excavation as ground settlements indicated. Besides, no local collapse, cracks or fissures take place during the period of excavation. In other words, all the archaeological information is preserved considerably well during archaeological excavation.

3. 3 Pore pressure and water level

Since discharging of the phreatic water imposes substantial effects on excavation behaviors, the development of phreatic water levels and the measured pore pressures are closely monitored during the excavation. Fig. 9 presents the development of the measured pore pressure at P1 (east side), P2 (south side) and P3 (west side) at the depth of 1.5 m. The pore pressure drops sharply from a positive value to a negative value during the first day. Afterwards, it decreases slowly with only occasional oscillation. From the observation, it can be concluded that soil has been consolidated while discharging the phreatic water, which is beneficial to the stability of test square during excavation. Due to the effect of initial excavation, data from the phreatic water level on the first day was not obtained.

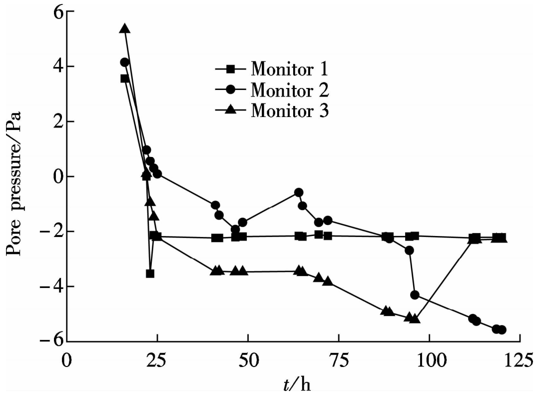

Fig. 9 Time histories of pore pressure at different points

The available data displayed in Fig. 10 indicates that the phreatic water level is maintained at $D = 2.0$ m as expected. Overall, the phreatic water was dewatered very successfully during the excavation period, which was also facilitated by the pore pressure results. Although the ground water table remains stable during excavation, pore pressure shows slight fluctuation, which means that consolidation of soft soil is still undergoing. As a matter of fact, consolidation of soft soil can take a long time even with the drainage measure. Hence, more attention should be paid to long-term stability considering the subsequent consolidation that affects the stability of the modeled test square.

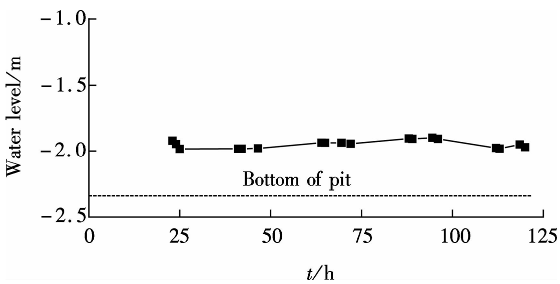

Fig. 10 Time histories of water table level

From the point of view on archaeological excavation and preservation of cultural information, the reason why the modeled test square remains stable during excavation is mainly due to the protection shield that prevents rainfall and dewatering action. Therefore, the results from the modeled test square for prehistoric earthen sites prove that the studied excavation method is suitable for the archaeological excavation and the presence of Liangzhu prehistoric sites or similar sites in the same area.

4 Conclusions

1) Monitoring plays an important role in the stability of archaeological excavation and preservation of cultural information as well as in further research on the shape optimum of the test square.

2) Ground settlement generated by dewatering and unloading action has no direct influence on the stability of the test square in terms of its maximum value. Similarly, although lateral displacement on four sides shows a nonlinear variation along the depth, the occurring maximum value during excavation does not cause the collapse of the test square or damage to cultural information. Monitor results from water level and pore pressure prove that consolidation of soil mass needs more time. As a result, long-term stability of the test square should be taken into account.

3) As important preventive environmental control measures, both the building of the protection shield and dewatering of the test square in advance largely contribute to the stability of the test square during excavation.

4) The investigation results presented in this study show that the proposed excavation methods can meet the requirements of archaeological excavation in Liangzhu prehistoric sites.

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史前土遗址模拟考古探方发掘期间的稳定性监测和评价

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摘要:为了研究考古开挖过程中的探方稳定性,以杭州地区良渚遗址为例,开挖了长、宽为 5 m,深度为 2.3 m,中间附带考古柱的模拟考古探方.在开挖过程中实时监测探方和邻近区域的稳定性参数,包括地面沉降、侧向位移、孔隙水压力和地下水位监测.监测数据表明,由于降水和探方侧边卸荷引起的地面沉降基本上随着离探方边缘距离的增大而减小,探方四边的侧向位移显示也沿深度方向的非线性变化且最大侧向位移值满足稳定性要求.孔隙压力和水位数据的变化表明,软土地区土体固结速率较慢,探方开挖之后的长期稳定性监测显得十分重要.同时,模拟探访发掘证明了台阶状开挖可以比垂直开挖更有效地减少侧向位移.模拟试验对于杭州良渚遗址的正式考古发掘提供了参考价值.

关键词:史前土遗址;考古发掘;模拟探方;稳定性监测

中图分类号:K854.1