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Geotechnical research on Jiangnan Tu-Dun tomb historical remains in China*

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Abstract: Geotechnical research on historical remains can provide new data and distinctive viewpoint for research on soil mechanics. Two Jiangnan Tu-Dun tombs historical remains were investigated by means of in situ and laboratory geotechnical tests. In the present paper the geotechnical properties of these man-made earthworks, especially ageing effect on consolidation and direct shear, and compaction properties of earth fill are discussed.

Key words: Tu-Dun tomb, Geotechnical investigation, Compaction, Ageing effect, Hangzhu technique
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INTRODUCTION

Historical remains were normally made from soil or rocks, and constructed in/on the ground; so it did not come as a surprise when they were found to be related to geotechnics. On the other hand, since these historical remains often contained long-term information on property change and stability change of earthworks, analysis of such information may help to clarify some ageing effects problems in soil mechanics (Nishida, 1992). This geotechnical engineering research investigated the earth fill characteristics and construction techniques employed in the construction of the Jiangnan Tu-Dun tombs, and will provide new data for research on soil mechanics, such as ageing effect, compacted soil.

Tu-Dun tomb is often mound-shaped and constructed with soil. Mainly constructed during the Bronze-Age period in Chinese history (about B. C.1200−B.C.222), Tu-Dun tombs are located exclusively and extensively in the Jiangnan area (Lu, 2002). The common construction process was: first the ground was cleaned and leveled, then, the dead were laid directly on the ground. In some cases, before placing the dead, the ground surface was specially treated to make a so-called “bed” of stones or burned soil. Finally, soil from the surroundings was put over it to form a mound. We will focus discussion on a large-scale Tu-Dun tomb in Anji and a small Tu-Dun tomb, named J-1.

GEOTECHNICAL RESEARCH ON THE TU-DUN TOMB IN ANJI

Generation

The large-scale Tu-Dun tomb investigated was archaeologically judged to be built during the later Spring-Autumn Period and is numbered D141 (Lu

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et al., 2002). It had height of about 8.0 m and elevation of about 40 m above sea level, an elliptical plane, from north to south about 50 m along the major axis, from west to east about 40 m along the minor axis.

During in situ investigation we made use of the eastern partially cut out section to excavate a trench vertically from the top of the tomb to the bottom so that we can get the full view of the earth fill structure. Meanwhile, during the process of excavating the trench, undisturbed samples AJ1−AJ7 were also obtained. Undisturbed samples were also obtained by boring sampling.

In situ investigation results and discussion

According to in situ observation and results from various tests, the assumed cross section of the earth fill was as shown in Fig.1. As indicated, the earth fill of this tomb can be divided into four sections, which are surface soil, rammed soil, red sandy soil and grey clay (Lu, 2002).

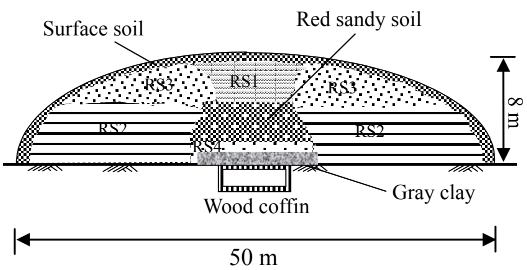

Fig.1 Assumed cross section of earth fill of Tu-Dun tomb D141

1. Surface soil

The about 1 m thick surface soil was dark brown to light brown downwards because of the external influence of natural factors on it, such as rain, wind, human activities, plants, etc. Particles of charcoal were found to be scattered within this layer. As shown in Table 1, the portion of clay and silt particles approximates to 85%. Therefore the soil in this layer is classified as CL, i.e. clay of low liquid limit.

2. Rammed soil

The term "ram" here corresponds to the conception of "compact" in the geotechnics sense. And this term is often adopted to archaeologically describe the action of Hangzhu, which is a kind of practical and effective soil construction method employed in construction projects ranging from dwellings, to city walls, foundations, and dams and tombs in ancient China, as well as in ancient Japan (Onitsuka *et al*., 2002a). Analysis of the cross section and test results of the earth fill revealed that this traditional Hangzhu technique was applied in constructing the earth fill of the tomb. The rammed earth fill of Tu-Dun tomb D141 can be assorted into four parts, i.e. RS1, RS2, RS3 and RS4 (Fig.1).

In RS1, the carefully compacted layer-state earth fill was clearly shown with each about 10−15 cm thick layer. Fine gravel and sand were also found mixed into this compacted soil. These are key features of the Hangzhu technique. The grain size distribution of sample AJ-4 sampled in this section clearly showed that the grain size distribution of this sample was conspicuously distinct from that of other samples; that is, the proportion of sand, silt and clay was almost identical and the proportion of gravel was outstandingly greater than that of the other samples. Consequently, well-graded state of grain size distribution was achieved and earth fill under this state could be compacted far more densely. Moreover, referring to Fig.2, the peak of N value from Standard Penetration Test also appeared in this part, all of which indicated that this section

Table 1 Physical properties of undisturbed samples from Tu-Dun tomb D141

Sample	Depth (m)	G_s	w_n %	ρ_t g/cm^3	ρ_d g/cm^3	I_p	Grain size distribution(%) gravel	sand	silt	clay	Class.
AJ-1	1.00	2.69	16.8	1.64	1.40	13.8	2.7	12.0	51.2	34.1	CL
AJ-2	1.80	2.69	17.0	1.73	1.48	12.9	2.2	10.4	49.6	37.8	CL
AJ-3	2.75	2.70	19.6	1.76	1.47	12.8	5.7	14.9	57.9	21.5	CL
AJ-4	4.00	2.70	15.9	1.96	1.74	13.9	9.6	29.7	29.8	30.9	CL
AJ-5	5.35	2.66	14.4	1.93	1.64	6.9	2.5	47.7	30.1	19.7	SF
AJ-6	6.50	2.66	23.3	1.85	1.50	11.5	0.5	14.8	50.3	34.4	CL
AJ-7	7.40	2.69	20.8	2.06	1.70	9.1	0.0	3.5	49.6	46.9	CL

was carefully compacted and attained a rather dense state. With regards to function, this section of soil strengthened the entire structure of the tomb, also served as a successful waterproof measure to some extent due to its dense state.

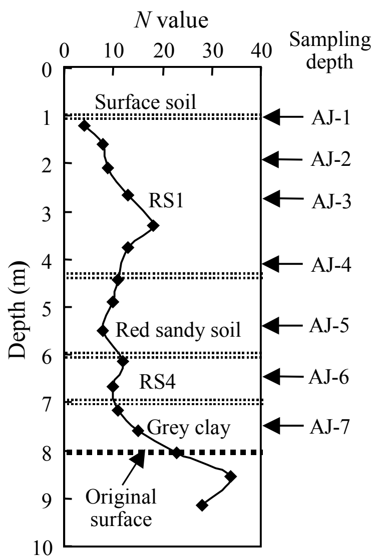

Fig.2 SPT results of Tu-Dun tomb D141 and sampling depth

From the cross-section, we can see that RS2 is another typical Hangzhu earth fill. Between the 10−15 cm thick layers of cohesive soil, 3−5 cm thick red sandy soil layers were sandwiched. Owing to the excellent permeability, sandy soil layers absorbed surplus moisture contained in the adjacent cohesive soil layers when these layers were compacted. Thus, along with this drainage of moisture that originally existed in the void spaces between soil particles, the soil particles became closer and a much denser state could be reached. Moreover, since sandy soil layers have inherently higher compressive strength than cohesive soil layers, the total strength of this section was enhanced. Because these layers of red sandy soil also formed a continuous plane extending to the edge of this tomb, it is assumed that the layers of red sandy soil may also drain off the water that seeped inwards the edge of the tomb.

RS3 is considered to be a mixture of surplus consisting cohesive soil, red sandy soil and grey clay left over during construction of the tomb. RS4 was made up of cohesive soil, acting as an interim layer between sections of red sandy soil and grey soil in the central section of the tomb.

3. Red sandy soil

The red sandy soil had a trapezoidal cross section and was composed of purplish red sand, classified as SF (namely, fine sand) according to the soil classification criterion based on grain size distribution (Table 1). As for the function of this section, since sandy soil has higher permeability of water, by the means of setting up this layer, water permeating from upper layers can be diverted to the periphery of the tomb. Additionally, since sandy soil has high strength itself, setting up this section also improved the stability and durability of the whole tomb.

4. Grey clay

The grey clay often functioned as hermetical and waterproof material to cover the central part of ancient tombs in China, and generally can be gathered from rice paddy fields. Table 1 shows that the proportion of silt and clay of sample AJ-7 sampled in this section accounted for 96.5%. In addition, as listed in Table 2, the dry density of the undisturbed sample in this part was 1.70 g/cm^3; while the resulting maximum dry density in laboratory compaction test was 1.71 g/cm^3; so the degree of compaction, which is defined as the ratio of natural dry density to maximum dry density, reaches 99.4%. Although ageing effect could also contribute to this high degree of compaction, careful compaction conducted then must predominantly contribute to it. All of the above results tell us that this section had achieved an extremely dense state that leads to considerably low permeability of water in this section so that the wood coffin can be preserved in dry condition as far as possible.

Table 2 Results of compaction test of Tu-Dun tomb D141

Soil sample	ρ_{dmax} g/cm^3	w_{opt} %	ρ_d g/cm^3	w %	Compaction degree %
Above 4 m	1.76	17.7	1.59	17.3	90.2
Red sandy soil	1.95	12.7	1.75	14.4	89.7
Grey clay	1.71	19.3	1.70	21.1	99.4

Laboratory test and discussion

The physical test results are listed in Table 1. Except that AJ-5 from the red sandy soil was classified as SF (fine sand), all the other samples were classified as clay. In the compaction test, three earth fill samples tested were mixtures of earth fill samples from the upper 4 m part of the trench, red sandy soil and grey clay respectively. Table 2 shows that the compaction degree of all these samples exceeded 90%, 99.4% in the case of grey clay. This rather dense state can match that of construction projects employing modern machines.

GEOTECHNICAL RESEARCH ON THE TU-DUN TOMB IN JINTAN

Generation

This Tu-Dun tomb designated as J-1 here is about 4.5 m in height, 20 m in diameter, and archaeologically concluded that this tomb was constructed during the early period of Spring-Autumn Period (Onitsuka *et al.*, 2002b).

In-situ investigation results and discussion

Samples from boring revealed that the color of the earth fill varies with the depth, although the properties of the whole earth fill are nearly identical. The earth fill illustrates a dark-brown in the upper part due to the nature environmental influences, such as rain, plant matter and so forth. In the center part the earth fill illustrate a brown to pale-brown. Owing to approaching incompletely weathered base soil, the bottom part shows a red-brown. SPT test results can be seen in Fig.3.

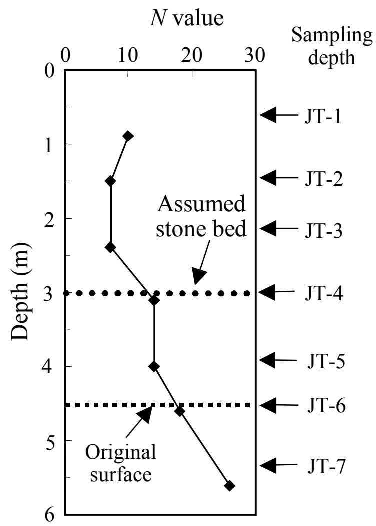

Fig.3 SPT result of Tu-Dun tomb J-1 and sampling depth

Laboratory test and discussion

1. Physical test

Table 3 is a summary of basic properties of the earth fill samples numbered from JT-1 to JT-7 sampled by boring (Fig.3). The data clearly show that for all the tested samples the percentage of silt plus clay exceeded 95%; so the earth fill of the tomb was categorized as CL.

2. Compaction test

The sample for compaction test was a mixture of earth fill from the upper 3 m part of the tomb. During the test, three different levels of compaction energy were adopted: standard effort (550 kN-m/m^3, 25 blows/layer), reduced effort (330 kN-m/m^3, 15 blows/layer), and modified effort (1100 kN-m/m^3, 50 blows/layer). Fig.4 shows that the maximum dry density and optimum water content in cases of standard effort and modified effort were about same; and

Table 3 Physical properties of samples from Tu-Dun tomb J-1

Sample	Depth (m)	G_s	w_n %	ρ_t g/cm^3	ρ_d g/cm^3	I_p	Grain size distribution (%)				Class.
							gravel	sand	silt	clay	
JT-1	0.6/0.8	2.71	22.9	1.84	1.50	20.2	1.1	1.6	45.4	51.9	CL
JT-2	1.3/1.5	2.71	25.1	1.97	1.57	20.9	1.2	2.6	44.8	51.4	CL
JT-3	2.0/2.2	2.71	24.7	1.83	1.47	20.8	1.3	2.8	49.8	46.1	CL
JT-4	2.8/3.0	2.70	24.7	1.90	1.52	16.4	1.6	3.0	54.3	41.1	CL
JT-5	3.8/4.0	2.72	26.0	1.99	1.58	20.6	1.2	1.8	49.6	47.4	CL
JT-6	4.4/4.6	2.71	21.6	1.98	1.63	17.6	0.2	1.1	52.7	46.0	CL
JT-7	5.3/5.5	2.70	21.5	2.03	1.67	16.7	1.0	1.9	57.0	40.1	CL

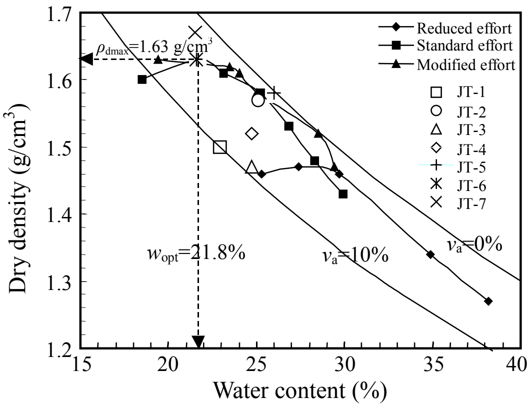

Fig.4 Result curve of compaction test on Tu-Dun tomb J-1 in JinTan

that maximum dry density was 1.63 g/cm^3, and optimum water content was 21.8%. In addition, the dry density and water content of undisturbed samples JT-1 to JT-7 are also marked in this figure clearly indicating that all the samples had less than 10% volume ratio of air void. The compaction degrees of the undisturbed samples were also calculated: JT-1 was 93%, JT-2 was 96.3%, JT-3 was 90.2% and JT-4 was 93.3%. Thus it was obvious that the earth fill of the tomb achieved rather dense state.

3. Direct shear test

Four kinds of samples were tested: undisturbed unsoaked sample (abbreviated as U_u), undisturbed soaked sample (U_s), compacted unsoaked sample (C_u) and compacted soaked sample (C_s). Herein compacted samples were those samples made by compaction with water content and dry density identical to undisturbed samples. Under condition of no swelling, the samples were soaked for 24 hours in the direct shear box. The shear speed was 0.8 mm/min; and 20, 40, 80 and 160 kN/m^2 are adopted as the vertical loads. The vertical loads were chosen due to consideration of the relatively small vertical effective stress within the tomb.

The relationship of the depth from the top of Tu-Dun tomb J-1 *vs* shear strength parameters c and φ are shown respectively in Figs.5a and 5b. The cohesion of U_u samples varied from about 80 kN/m^2 to 180 kN/m^2 being much greater than that of C_u samples as a whole. From Fig.5a we can also note that the cohesion variance between U_u and U_s was smaller than that between C_u and C_s. These results can be explained as about 2000 years ageing effect on cohesion.

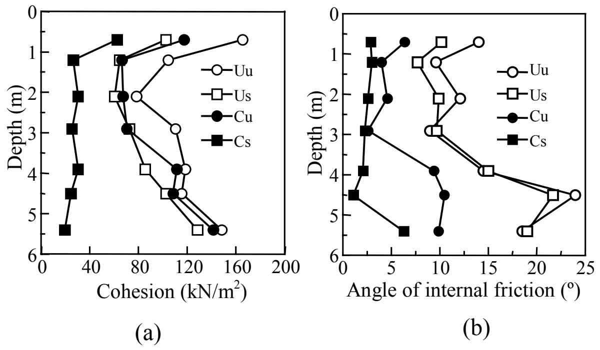

Fig.5 Direct shear test results of Tu-Dun tomb J-1 showing the relationship of the depth from the top *vs* shear strength parameters *c* (a) and *φ* (b)

As to the angle of internal friction φ, it is shown in Fig.5b that φ of U_u samples was larger than that of C_u samples. Similar to the previous analysis of cohesion, the variance of φ between U_u and U_s was smaller than that between C_u and C_s. It appeared that for the earth fill of Tu-Dun tomb J-1, ageing effect exerted similar influence on change of the cohesion and angle of internal friction.

4. Consolidation test

Besides undisturbed samples, compacted samples with water content and dry density identical to the undisturbed sample were also tested to investigate the ageing effect on consolidation characteristics of the earth fill. The p_c results are plotted in Fig.6 clearly showing that the undisturbed samples bare bigger p_c than compacted samples. The consolidation pressure *vs* compression index C_c^* of the undisturbed and compacted sample JT-3 is shown

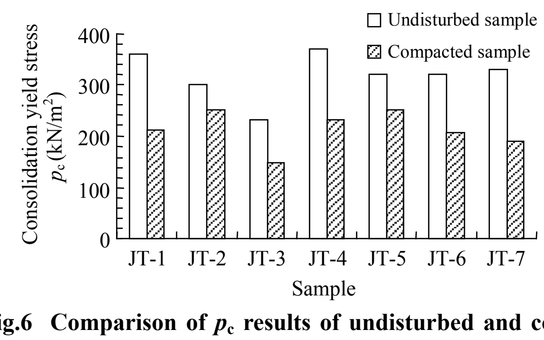

Fig.6 Comparison of p_c results of undisturbed and compacted samples

in Fig.7. Here, C_c^*, expressed by the equation $\Delta e/\Delta \log p$, was calculated at every consolidation pressure in the e-log$p$ curve. We can note that near p_c of the undisturbed sample JT-3 C_c^* has a distinct peak, whereas C_c^* of the compacted sample has no such obvious peak. The other sections of the two curves, however, are close to each other. Mesri and Godlewski (1977) argued that for natural clay the difference between undisturbed sample and remolded sample on consolidation characteristics is that whether a peak appears in the relationship of consolidation pressure *vs* compression index C_c^* due to ageing effect. So from the test results illustrated above, it can be concluded that the ageing effect on the consolidation characteristics of this man-made earth fill is similar to that of natural clay. This can be attributed to the fact that the earth fill had existed for about 2500 years and behaves as naturally deposited clay.

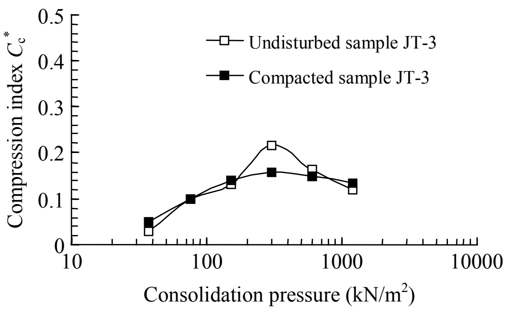

Fig.7 C_c^* *vs* consolidation pressure

CONCLUSION

With respect to engineering properties, we see that the earth fills of these two tombs overall had a rather dense state. For Tu-Dun tomb J-1, all the undisturbed samples had volume of air void of less than 10% and average compaction degree of about 93%. For Tu-Dun tomb D141, compaction degree as a whole exceeded 90%.

In this work we also studied the ageing effect on the man-made earth fills of these tombs. Consolidation test results showed that the p_c of undisturbed sample which came into being about 2000 years ago were bigger than that of compacted samples. Moreover, it also appeared that the higher the compaction degree of the earth fills, the more remarkable the ageing effect on p_c. In studying Tu-Dun tomb J-1, the ageing effect on compression index was also analyzed. The ageing effect on the cohesion of the soil was clearly shown through direct shear test results. It was also indicated by the results of Tu-Dun tomb J-1 that the ageing effect caused the change of internal friction angle to be similar to that of cohesion.

This study revealed that a kind of ancient construction method (Hangzhu technique) was used in Tu-Dun tomb D141. When considering enduring durability, the Hangzhu technique was often adopted in constructing a tomb. Furthermore, through this research, we know that people had known that by making use of specific kinds of soil, some engineering requirements could be fulfilled. For example, using sand as drainage materials, and using clay as waterproof materials.

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