Mechanical Response of Consolidation State to Soil between Underwater Compaction Piles Strength Recovery

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ABSTRACT

During the analysis of soil strength between piles in composite foundation with gravel column, the consolidation state of the undisturbed soil should not be neglected. Underwater sand compaction piles are adopt to treat soft foundation in the Hong Hong-Zhuhai-Macao bridge engineering which provides an opportunity to study composite foundation's characteristics and the mechanical property of the soft soil. In order to declare the strength increase- process of soil between piles in composite foundation, the high pressure consolidation test, vane shear test and standard penetration test are achieved. What's more, the effective additional stress (p_0) of the overlaying soils and over-consolidation ratio (*OCR*) are calculated with statistical data. On the basis of the least square method, the linear equation between undrained shear strength (C_u) and test depth (*H*) are obtained. The result shows that pile driving can change the consolidation state of soil between piles, that's to say, the under-consolidation soil can convert to over-consolidation soil, and the over-consolidation soil can convert to under-consolidation soil too. In addition, when the replacement rate is 25.6%, strength growth rate of under-consolidation soil between piles ranges from 16.4% to 80%.When the replacement rate is 55%, strength growth rate of over-consolidation soil between piles will become 19.4%.Considering the influence of test time, when the lasted time is 2 months, strength growth rate of under-consolidation soil between piles will become 13.2%~27.3%. When the lasted time is 6 months, the strength growth rate keeps stable growth. When the time is 12 months later, the strength growth rate will increase to 164%. The obtained results can provide the foundation treatment experience for geotechnical engineers and the best time for the strength of pile testing.

KEYWORDS: over-consolidation ratio (*OCR*); high pressure consolidation test; vane shear test; underwater sand compaction piles (SCP); soil between piles; the Hong Hong-Zhuhai-Macao bridge engineering

INTRODUCTION

Research on composite foundation bearing capacity [1-5] becomes very popular and necessary in geotechnical engineering, especially the analysis of discrete material pile strength. The mechanism of rigid pile-soil cooperation differs from discrete material pile that the maximum elasticity modulus ratio value of rigid pile-soil (E_{pile} / E_{soil}) can reach 120, which indicates that soil between rigid piles almost does not provide bearing capacity for composite foundation. Otherwise, the maximum stress ratio of discrete material pile-soil ($\sigma_{pile} / \sigma_{soil}$) only can arrive to 8, which shows soil between discrete material piles provides part of the bearing capacity. Zhang J P, et al. (2013) got the regulation that dynamic penetration curved change with time and the feature that soil between piles increased with time. After 14 days, the effect test could be operated when the soil pore water pressure fully dissipated. Yao X Q (1997) demonstrated that the estimation of pile's capacity which increased with time could be made by means of the calculation for the consolidation of soil among piles. Wu C F and Guo W C (2015) obtained that the pile- soil stress ratio in the neutral surface was proportional to the internal friction angle of soil, cohesion, pile-soil friction angle, pile diameter, pile length, pile side friction etc and inversely to the pile spacing. Liu P and Yang G H (2011) demonstrated that the rational design of composite foundation should consider the deformation compatibility and bearing capacity of soft soil should be determined under corresponding the settlement in terms of its *p-s* curve.

Many conclusions come from the research on stone columns composite foundation, but the study of underwater sand compaction piles and soil between piles appears rarely. According to the Hong Hong-Zhuhai-Macao bridge engineering, the mechanical response of consolidation state to soil between underwater compaction piles strength recovery can be achieved on the site test and mathematical calculation.

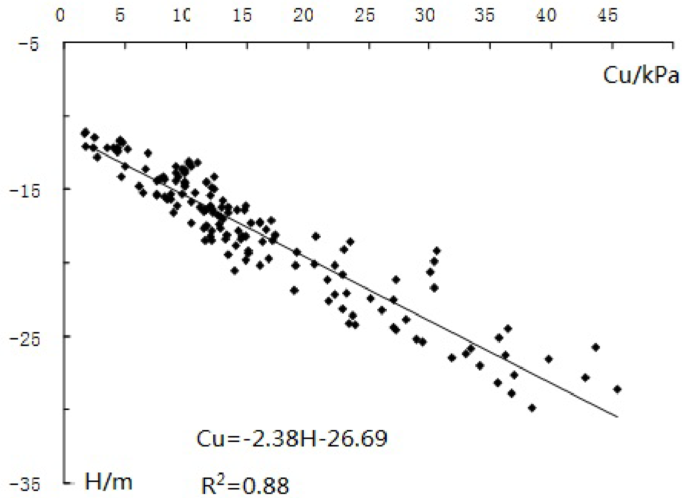
BACKGROUND OF ENGINEERING AND RESEARCH

In the Hong Hong-Zhuhai-Macao bridge engineering, underwater sand compaction piles are adopt to reinforce its soft foundation of the eastern artificial island, which is divided into two areas A and C. Considering the reinforcement effect, the high pressure consolidation test, vane shear test and standard penetration test are achieved to soil between piles, which provides such a various test data for us to study soils strength recovery and consolidation state. In addition, indoor experiments are carried out to obtain the soil physical and mechanical indexes, which do benefits to the research on soil strength recovery. On basis of experimental data, the mechanical response of consolidation state to soil is achieved.

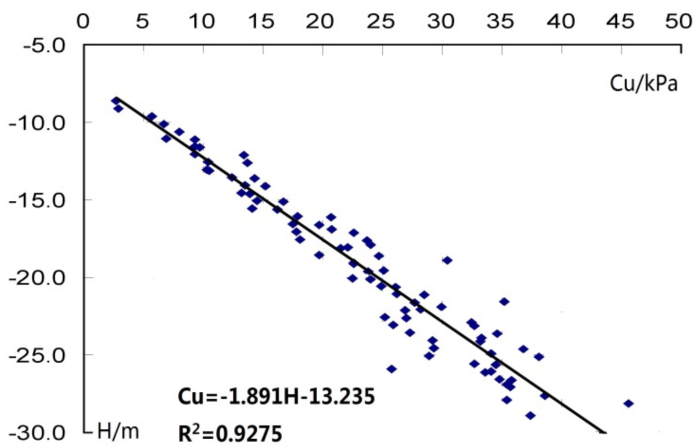
STRESS HISTORY OF SOILS

Vane Shear Test

In order to analyze the stress history of soils, the vane shear test was operated in11 drill position of east artificial island. In order to ensure the precision of vane test data, the test condition was chose by the small waves, gentle flow (high, low tide and the tidal) during the test period, in addition, the casing pipe controller are adopted at the bottom.



(a) Replacement rate=25.6% in area C



(b) Replacement rate=55% in area A

Figure 1: Linear relationship between (C_u) and test depth (H)

During the treatment of vane shear test results, the relation curve between undrained shear strength (C_u) and test point elevation (H) are drew and the test data in eastern artificial island is statistically analyzed according to test point elevation. In order to determine the change rule between undrained shear strength and test point elevation ($C_u \sim H$), all the test point results are operated for linear analysis according to the least square method, as shown in Figure 1(a). The calculated result indicates that when the replacement rate in area C is 25.6%, the cross board test results of different elevation are with smaller discreteness, the shear strength grows with the increase of the test depth. The vane shear test results C_u value and the test point elevation shows a good linear relationship, for the reason that the correlation coefficient for R^2 = 0.88. Therefore, the soils in test site can concluded as under-consolidation soils from the linear relation.

Similarly, when the replacement rate in area A is 55%, undrained shear strength of undisturbed soils are analyzed in linear relation based on depth by using the least square method, as shown in Figure 1(b). It turns out that the soils of area A in eastern island are also under-consolidation soils.

High Pressure Consolidation Test

The high pressure consolidation tests of major soft clay soils are took to the eastern artificial island, over-consolidation ratio (*OCR*) value of each soil layer is obtained by calculation, which has been carried on the statistics, the stratified results are shown in Table 1 and Table 2. On the basis of vane shear test results, calculation of every soil layer over-consolidation ratio is achieved for further detailed analysis of the soil stress history.

OCR, over-consolidation ratio, which is also called early consolidation ratio. *OCR* refers to the ratio which is between the largest ever been consolidation pressure (p_c) of history and current consolidation pressure (p_0). According to the size of the ratio, the soil consolidation state can be classified into three categories: when $p_c / p_0 = 1$, the state is normal consolidation; when $p_c / p_0 > 1$, the state is over-consolidated condition; when $p_c / p_0 < 1$, the state is under-consolidated condition, which is shown in Equation (1).

$$OCR == \frac{p_c}{p_0} \tag{1}$$

In this equation, p_c is the largest ever been consolidation pressure of history, p_0 is the existing soil gravity pressure.

Table 1: Statistics results of all soil layers’ OCR value in area C

soil layer	number of samples	maximum value	minimum value	standard deviation	variable coefficient	average value
①$_1$ silt	2	0.89	0.72	0.12	0.15	**0.81**
①$_2$ silt	9	0.87	0.5	0.13	0.19	**0.69**
①$_3$ silty clay	6	0.88	0.44	0.18	0.28	**0.64**
②$_1$ clay	9	2.78	0.84	0.65	0.34	**1.9**
③$_1$ silty clay	11	0.98	0.61	0.11	0.13	**0.84**
③$_{1-1}$ clay	11	0.95	0.66	0.1	0.12	**0.81**
③$_2$ silty clay with sand	2	1.28	0.99	0.21	0.19	**1.13**
③$_3$ silty clay	1	—	—	—	—	**0.98**
④$_7$ silty clay	2	0.94	0.91	0.02	0.03	**0.92**

Based on the mathematical statistics theory, Table 1 shows that the under-consolidation state soil layers in area C of eastern island are consist of ①$_1$ silt, ①$_2$ silt, ①$_3$ silty clay, ③$_1$ silty clay and ③$_{1-1}$ clay. The normal consolidation state soil layers are consist of ③$_2$ silty clay with sand, ③$_3$ silty clay and ④$_7$ silty clay. The over-consolidation state soil layer is ②$_1$ clay.

Table 2: Statistics results of all soil layers' OCR value in area A

soil layer	number of samples	maximum value	minimum value	standard deviation	variable coefficient	average value
①$_1$	20	1.61	0.68	0.23	0.24	**0.94**
②$_1$	12	2.79	1.08	0.47	0.31	**1.52**
③$_1$	18	3.85	1.05	0.82	0.38	**2.16**
③$_2$	26	2.25	0.9	0.42	0.28	**1.49**
④$_1$	4	1.51	0.96	0.23	0.19	**1.19**

Table 2 shows that the over-consolidation state soil layers in area A of eastern island are consist of ②$_1$, ③$_1$, ③$_2$ and ④$_1$. The normal consolidation state soil layer is ①$_1$ clay.

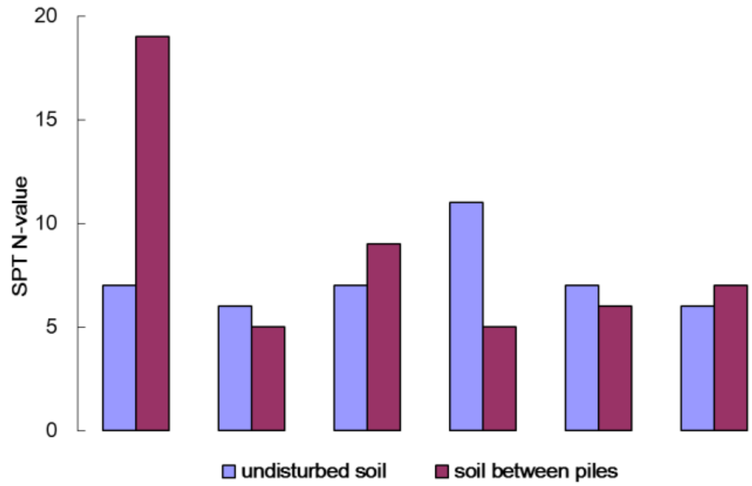
CONSOLIDATION STATE INFLUENCE TO STRENGTH OF SOIL BETWEEN PILES

Change of the Soil Strength

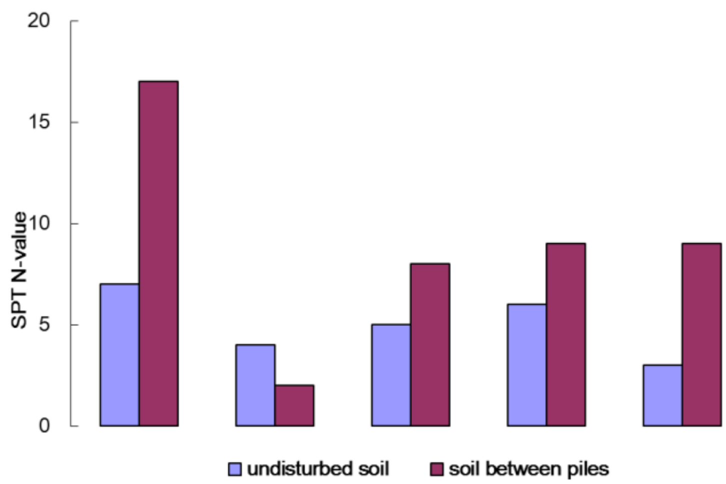
Under-consolidation state:

The displacement rate calculation depends on two important factors which contains the space and diameter between two piles of underwater sand compaction piles. According to the early formation drilling data, the strength parameters of the undisturbed soil and soil physical and mechanical indexes can obtained. After the completion of the piling, the standard penetration test has carried on soil between piles, combined with the soil consolidation state, the soils strength recovery is to study by comparison on the original soil layer in the same position after pile driving.

When the replacement rate of the composite foundation is 25.6%, the statistical results are shown in Figure 2.



(a) ③$_{1-1}$ soil layer



(b) ③$_{1}$ soil layer

Figure 2: SPT N-value comparison between undisturbed soil and soil between piles

It turns out that ③$_{1-1}$ soil layer is under-consolidation state which the SPT N-value of undisturbed soil is 7.3 on average, after the piling, the SPT N-value of soils between piles grows to 8.5 on average. According the two values, the strength increase rate of soil between piles is 16.4%. By the same way, ③$_{1}$ soil layer is under-consolidation state which the SPT N-value of undisturbed soil is 5 on average, after the piling, the SPT N-value of soils between piles grows to 9 on average. According the two values, the strength increase rate of soil between piles is 80%.

Take the standpoint of stress history, the soil strength between piles can be analyzed further in detail by considering the effective additional stress (p_0') of the overlaying soils and over-consolidation ratio (*OCR*).

XKD42 drilling data can declare the formation of ③$_{1}$ soil layer. ③$_{1}$ overburden soil layer is 12.4m thick, take the average float severe (γ')9.8kN/m^3, the over-consolidation ratio (*OCR*) is

0.84, the pre-consolidation pressure (p_c) can be calculated as 104.2kPa. Because of the construction excavation, the scale height will change to -18m under water, and then the existing overburden thickness decreases to 4.5m. Therefore, by calculation with soil mechanics method the new over-consolidation ratio (*OCR*) is 2.31, which gathers than 1. Due to the subsequent excavation which causes the decrease of the stress, ③$_1$ soil layer becomes from a state of under-consolidation into over-consolidation, which demonstrates that sand piles enlargement and compaction causes soil strength growth.

Calculated another soil layer of ③$_{1-1}$ by the same method, XKD41 drilling data can declare the formation of ③$_{1-1}$ soil layer. ③1-1 overburden soil layer is 24m thick, take the average float severe (γ')10kN/m^3, the over-consolidation ratio (*OCR*) is 0.81, the pre-consolidation pressure (p_c) can be calculated as 194.4kPa. Because of the construction excavation, the scale height will change to -18m under water, and then the existing overburden thickness decreases to 6m. Therefore, by calculation with soil mechanics method the new over-consolidation ratio (*OCR*) is 3.24, which gathers than 1. Due to the subsequent excavation which causes the decrease of the stress, ③$_{1-1}$ soil layer becomes from a state of under-consolidation into over-consolidation, which demonstrates that sand piles' enlargement and compaction causes soil strength growth.

Over-consolidation state

According to the indoor test of *OCR* value, compare the undisturbed soil between piles and soil strength changes of the over-consolidated condition.

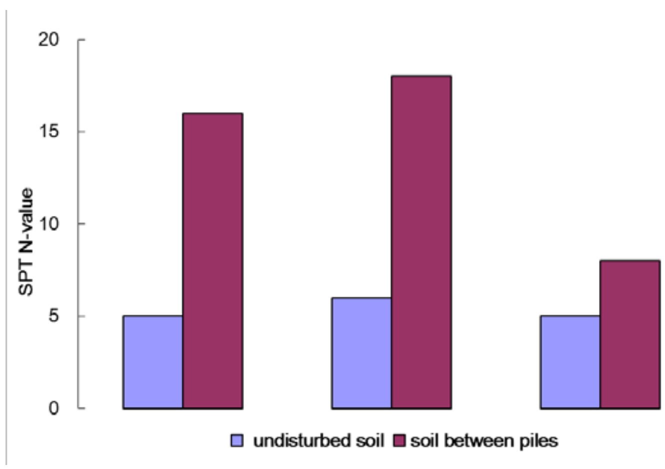


Figure 3: ②1 SPT N-value comparison between undisturbed soil and soil between piles

As shown in Figure 3, ②$_1$ soil layer is over-consolidation state which the SPT N-value of undisturbed soil is 5.3 on average, after the piling, the SPT N-value of soils between piles grows to 14 on average. According the two values, the strength increase rate of soil between piles is 164%. The state of over-consolidated soils will not change due to excavation of sand pile construction, but soils strength will reduce with the construction excavation. What's more, the compaction of sand pile hole enlargement process is equivalent to increase the lateral pressure of soil between piles, after super pore pressure dissipation, its strength will increase.

When the replacement rate of the composite foundation is 55%, compare the SPT N-values between undisturbed soil and soils between piles as shown in Figure 4.

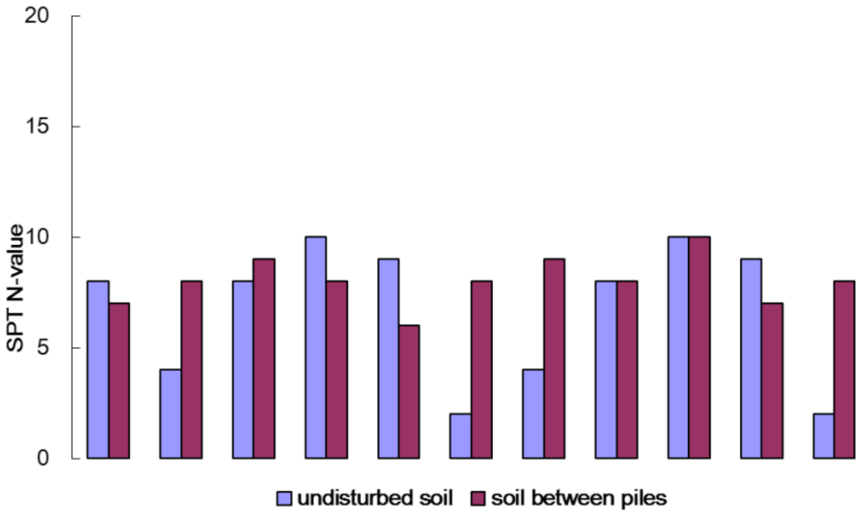


Figure 4: ③$_1$ SPT N-value comparison between undisturbed soil and soil between piles

It turns out that ③$_1$ soil layer is over-consolidation state which the SPT N-value of undisturbed soil is 6.7 on average, after the piling, the SPT N-value of soils between piles grows to 8 on average. According the two values, the strength increase rate of soil between piles is 19.4%. The state of over-consolidated soils will not change due to excavation of sand pile construction, but soils strength will reduce with the construction excavation. After super pore pressure dissipation, its strength will increase.

Influence of Effective Overburden Stress and Its Calculation

The overburden stress has influence on soil strength and consolidation state. From a view of pile forming process, sand pile is formed by compacting hole and enlargement, so the soil between piles will be affected by the compaction pile. According to Vesic expansion theory(Ke C T, et al., 2012), when the state is of limit equilibrium, there will appear a round hole periphery which contains a plastic zone and an elastic zone, soil elastic state, and the soils keep an elastic state as shown in Figure 5. The plastic zone of soil compactness increases and the porosity decreases due to compaction, but the soil in addition to the plastic zone remains its natural state.

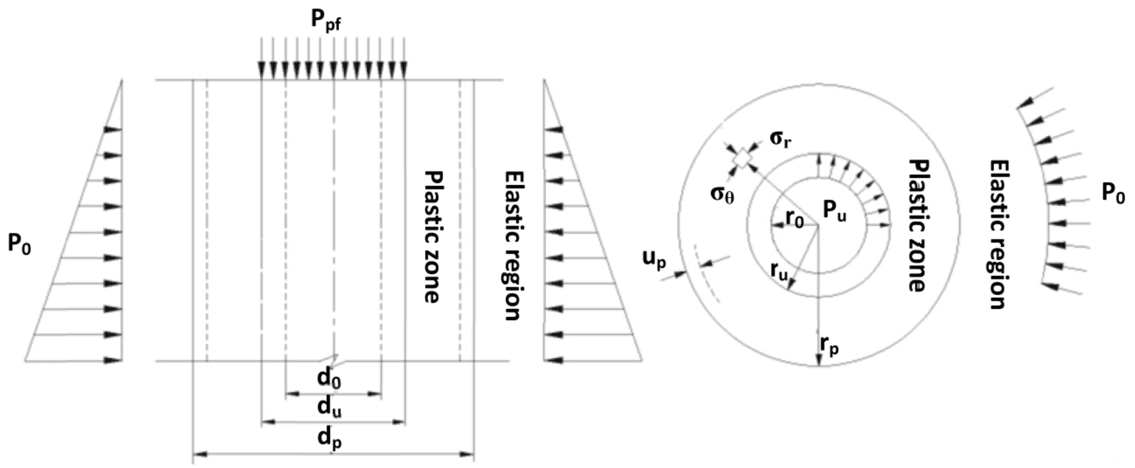


Figure 5: Mechanical model of discrete material pile

Besides, change of the overburden stress can vary the soil consolidation state. This is because the existing soil gravity stresses decrease or increase, which will make the *OCR* change. That's to say, the secondary consolidation can convert into a state of over-consolidation, or the over-consolidated condition goes into a secondary consolidation.

The effective overburden stress can be calculated according to the equation (2) ~ (5).

$$p_0' = p - \sigma_c \tag{2}$$

$$\sigma_c = \sum_{i=1}^{n} \gamma_i h_i \tag{3}$$

$$\gamma' \simeq \gamma - \gamma_w \tag{4}$$

$$\gamma_m = \frac{\sum \gamma_i h_i}{\sum h_i} = \frac{\gamma_1 h_1 + \gamma_1 h_1 + ... + \gamma_n h_n}{h_1 + h_2 + ... h_n} \tag{5}$$

In these equations, p_0' is the effective overburden stress (kPa), p is the total stress on average (kPa), σ_c is soil gravity stress (kPa), h is soil thickness (m), γ is soil dry weight (kN/m^3), γ' is soil submerged unit weight (kN/m^3), γ_w is water unit weight (kN/m^3), γ_m is soil weighted average unit weight (kN/m^3).

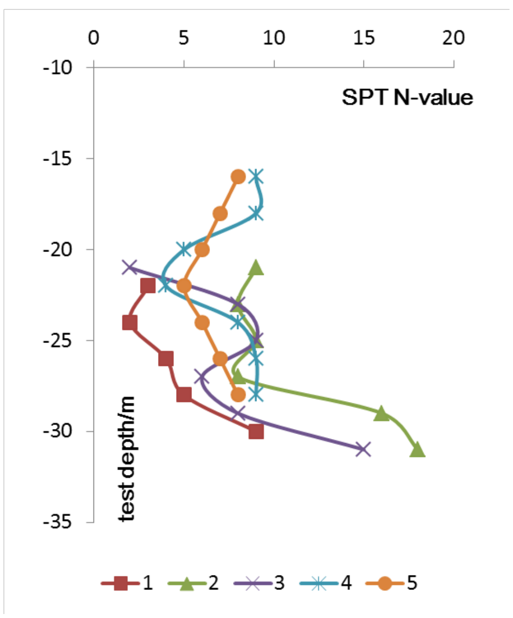
Table 3: Calculation of effective overburden pressure

location	soil	parameters	soil	parameters	soil	parameters	soil	parameters	p_0' (kPa)
C1-2	①$_1$	γ' =5.4 kN/m^3 h=3.1m	①$_2$	γ' =5.8 kN/m^3 h=5.9m	①$_3$	γ' =6.9 kN/m^3 h=0.5m	②$_1$	γ' =7.1 kN/m^3 h=5m	**89.91**
C12	①$_1$	γ' =5.4 kN/m^3 h=2m	①$_2$	γ' =5.8 kN/m^3 h=6m	①$_3$	γ' =6.9 kN/m^3 h=5m	①$_2$	γ' =5.8 kN/m^3 h=4.9m	**114.89**
C16-2	①$_1$	γ' =5.4 kN/m^3 h=6m	①$_2$	γ' =5.8 kN/m^3 h=12m					**102**
A8-3	①$_1$	γ' =5.4 kN/m^3 h=9m	①$_1$	γ' =5.4 kN/m^3 h=4.2m	②$_1$	γ' =7.1 kN/m^3 h=2.3m			**87.61**
A8-15	①$_1$	γ' =5.4 kN/m^3 h=15.5m	②$_1$	γ' =7.1 kN/m^3 h=3.2m					**123.94**

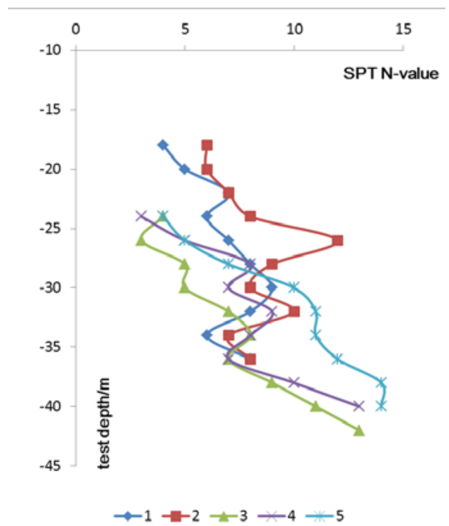
The calculated results of the effective overburden stress shown in Table 3 can use to evaluate soil stress history, and also do benefits on calculation of constraining force from soil to piles.

Relationship between Soil Strength and Test Depth with Time

In accordance with the different blocks between the same soil piles, the statistics of standard penetration test data is carried out. The relationship between N-value and test depth is analyzed in Figure 6.



(a) Replacement rate=25.6%



(b) Replacement rate=55%

Figure 6: Relationship between soil strength and test depth

It shows that the overall change law is consistent of soil between piles whenever the replacement rate becomes high and low. The compaction of sand pile diameter increased lateral pressure of soil between piles, which makes the N-value growing with the depth increasing.

Respectively, the under-consolidation and over-consolidated soil strength recovery is analyzed statistically when the replacement becomes 25.6% and 55%, which are shown in Table 4 and Table 5.

Table 4: Soil between piles' strength recovery when replacement rate = 25.6%

consolidation state	N-value of undisturbed soil	lasted time	N-value of soil between piles	growth rate of strength
under-consolidation	4.7	1 month	8.5	81%
	0		10	—
	7	4 months	18	157%
	6.5		7	8%
	0	12 months	9.8	—
	0		6.7	—
over-consolidation	5.3	12 months	14	164%

Table 5: Soil between piles' strength recovery when replacement rate = 55%

consolidation state	N-value of undisturbed soil	lasted time	N-value of soil between piles	growth rate of strength
under-consolidation	0	2 month	5.5	—
	0	3-4 months	5	—
	0	6 months	5.3	—
over-consolidation	6.8	2 months	7.7	13.2%
	6.6		8.4	27.3%

The results demonstrate that when the soil state is under-consolidation condition, the soil strength of high replacement rate grows stably that the N-value is 5 on average. And the soil strength of low replacement rate increases with time lasting. When the soil state is over-consolidation condition, the soil strength growth rate becomes 164% for 12 months later that the replacement rate is low. But the soil strength growth rate becomes 13.2%~27.3% for 2 months later that the replacement rate is high.

CONCLUSIONS

For thick silt and soft clay the high pressure consolidation test and cross plate test can determined the soil stress history condition, which must be taken into account when calculating the effective overburden stress of soil pre-consolidation pressure. Underwater sand compaction piles drilling will cause a disturbance of the undisturbed soil mechanics state in a certain extent, the *OCR* value change should be considered during the analysis of soil stress state.

Soils strength will grow no matter the consolidation state is under-consolidation or over-consolidation condition. And soil strength will increase with the test depth growing, which indicates that pile drilling can improve soil strength between piles.

When the replacement rate is low, the soil strength between piles with under-consolidation state will increase obviously by comparison of the undisturbed soil. What’s more, the soil strength with under-consolidation and over-consolidation state is growing rapidly over time. When the replacement rate is high, the soil strength with under-consolidation state will increase slowly over time, and soil strength with over –consolidation state will grow slowly, too.

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