Article no. 31

THE CIVIL ENGINEERING JOURNAL 3-2019

STUDY ON THE FORMATION MECHANISM OF BONDING LAYER AROUND PILE BODY IN SOFT CLAY

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ABSTRACT

After jacked pile is driven into the soft clay, a bonding layer would form a around pile body, it enlarges the pile side area and increases its bearing capacity effectively. At present, there are few reports about it. In this paper, the formation mechanism of a bonding layer was studied by theoretical analysis and field test. The results show that the soil particles adhering to a solid surface is an interface phenomenon, the adhesive force is related to soil moisture content, particle size and solid interface conditions. According to the theoretical analysis the bonding layer is the adhesion of tiny colloidal particles on pile surface and is the result of a disturbed soil becomes plastic body from plastic flow after water film disappears. Field test verified the theory and confirmed that the bonding layer was a pile-soil interaction, in the same clay, only the pile with coarse surface has the bonding layer. Finally, a microscopic test of soil samples was carried out, further explaining the formation mechanism of bonding layer.

KEYWORDS

Jacked pile, Soft clay, Bonding layer, Adhesion, Micro-structural analysis

INTRODUCTION

The jacked pile has been widely used in the soft clay because of its high efficiency, low environmental impact and high construction quality. The existing research shows that the bearing capacity of jacked pile increases with the rest time, which is called timeliness. [1~3] As the jacked pile is pressed into soft clay, the end resistance is basically unchanged but the side friction is time dependent due to the soil thixotropic recovery, later, a bonding layer would form close to the pile surface. The bonding layer enlarged the pile side area and cause the bearing capacity increase, the phenomenon is soil-shell effect [4] Due to the bonding layer is important for the optimizing design of pile foundation and the reducing of pile cost. This paper attempts to study the formation mechanism of the bonding layer by theoretical analysis, field test and micro-research. The purpose is to lay on a role for further studying the timeliness of the bearing capacity of jacked pile.

THE PROCESS OF PILE DRIVING

In soft clay, the piling process could be divided into three steps. At first, the pile tip breaks the soil particles to form a plastic flow, then the soil particles around pile body move sideways, finally the pile slides into the damaged soil. In this process, three parts of damaged areas would form around the pile body, as shown in Figure 1 [5]. The part I. is a completely remodelled area which is affected mostly by the pile driving, the range is about 0.2d (d refers to the diameter of pile), in the area the soil particles would cling to the pile body; outside of the part I. is the part II., a remodelling area, which is greatly affected by the pile driving, the range of it is about 1d; beyond it is the part III., an elastic compression zone, which is less affected by the pile driving. The formation of a bonding layer is related to soil disturbance, excess pore water dissipation and soil particles adhesion.

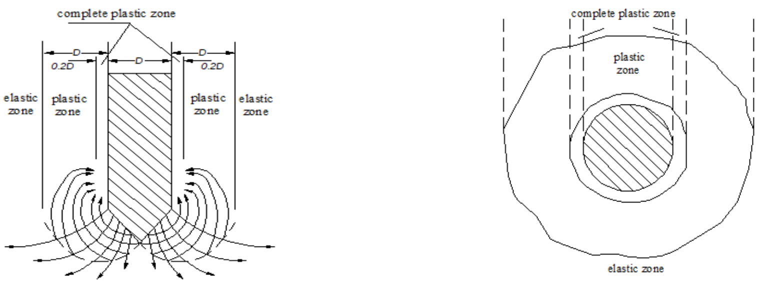


Fig.1 – Damaged area in clay

According to the Figure1, the penetration of a jacked pile would cause the disturbed soil to form strong disturbance zone, medium disturbance zone and weak disturbance zone along the radial direction of pile body. In the strong disturbance zone, clay is completely reshaped and forms a water film. In the course of pile driving, the excess pore water close pile body begins to dissipate, later the farther excess pore water dissipates [6]. With the dissipation of excess pore water, the concentration of water film will increase, the soil particles in it would form a new structure.

Due to the friction at pile-soil interface, most of the soil particles in shear zone are the colloidal particles and water film is muddy. With the pore water discharged, the colloidal particles gathered and formed a bonding layer adhering to the pile body firmly. The adhesion force between the fine clay particles and the pile surface is mainly determined by the number of sticking points. The more the cohesive points are, the greater the adhesion force is. Ren Lu-quan and other experts put forward the "plate-water-plate" system model and believed that the adhesion between soil particles and the solid surfaces mainly depends on the water-loop gravitation and water film viscous force. When the water content in clay is between the plastic limit and liquid limit, the adhesion on contact surface is the most serious [7]. If the water content in the soil is below the plastic limit, there are no capillary force and water viscous resistance between the approximately rigid clay and the solid, even under certain pressure conditions the adhesion force is also non-existent. If the water content is high and exceeds the liquid limit, the water film between the soil and the solid is very thick, the viscous force in fluid will reduce, the adhesion force decreases correspondingly.

THEORETICAL ANALYSIS OF CONTACT ADHESION

The soil-solid adhesion is a complex surface phenomenon. Researches about it began as early as in the eighteenth century. Some scholars proposed their theories from different perspectives to try to explain the adhesion phenomenon. These theories included the capillary theory of Akiyama Fung and Yokoi Hirai [8], the water film theory of Fountaina [9],the five-layer interface theory of Qian Dinghua [10], and the molecular model theory of Zhang Jixian [11].

Contact adhesion force

The ability of clay adheres to a solid surface can be quantified by the amount of adhesion. The more common view is that the adhesive force is generated by the medium of water film which is formed by the weakly bound water of soil particles. Some scholars believe that the molecular force alone could not sufficiently explain the nature of adhesion, and it is necessary to consider the charge action of colloids. According to literature [11,12], the adhesive force between soil particles and the solid surface could be divided into molecular gravitation, independent water ring gravitation and water film viscosity, but they changed with the interface state.

The scholar Zhang Ji-Xian [11] considered the soil-solid adhesive force as an algebraic sum which contains the following forces.

$$F = f_c + f_v + f_w \tag{1}$$

Where F is the total adhesive force; $\mathrm{f_c}$is the capillary force generated by the meniscus when free water infiltrated the soil particles and the solid surface, which was formed by the microscopic contact points; $\mathrm{f_v}$is the viscous resistance,which is the major component of adhesive force when water content was high and the meniscus was non-exist; $\mathrm{f_w}$is the “wedge open” force generated by the imbalance of interface liquid and the chemical potential, which tends to separate the interface and decrease the adhesive force.The three forces have different effects, in general, the viscous resistance $\boldsymbol{f_c}$ and capillary forces $\boldsymbol{f_v}$ are the main parts of the contact adhesion.

Contact adhesion mechanism

Soil adhesion is an interface phenomenon which refers to the soil particles attached to other materials surface. The soil-solid adhesion system involves soil, solid and the interface. In fact the soil adhesion is a common phenomenon. People have been studying the adhesion of soil to farming implements for a long time. Fountaina used a special device to test the adhesion mechanism of sand and clay particles on solid surfaces [10]. Figure 2 and Figure 3 are the diagrams of soil and solid surface adhesion. For a solid in sand, due to the sand is a coarse-grained soil and the surface of particles or agglomerates generally has a sharp corner, as the sharp corners touched the solid surface they would adhere each together in the action of discontinuous water ring, the adhesive force would exist in every contact point, the sum of all contact points cause the total adhesion force. For a solid driven in clay or other fine-grained soil, the water film between soil and the solid surface is the main part of the adhesion, because the water film is like a bridge, it results molecular attraction and additional bending, so the adhesive force in clay is related to the water tension, but the water tension is related to the thickness of the water film and the characteristics of the solid surface, the greater the water film thickness is, the smaller the water tension is. The adhesion force of sand is very small due to it depends on every contact point. Therefore, the obvious adhesion phenomenon usually occurs in clay. The particle size, mineral composition, water content, solid surface and other factors all have an important role on the adhesion.

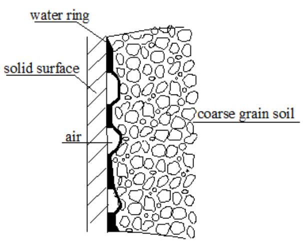


Fig.2 – Sand-solid adhesion

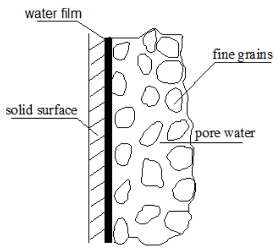


Fig.3 – Clay-solid adhesion

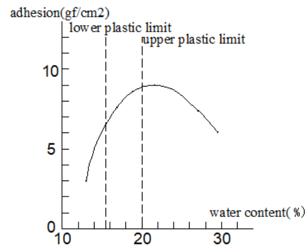
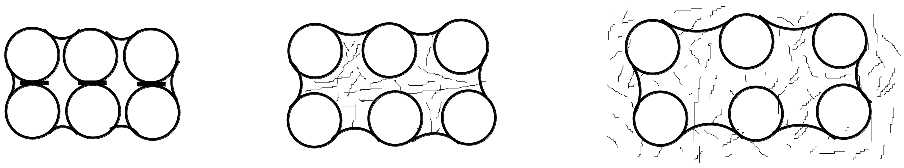


Fig.5 – Adhesion and water content

Generally, the water content in soil has four states.(1) Water content is lower than the plastic limit, only the strong bound water exists in the soil, and there is a discontinuous annular water film at every contact point, as shown in Figure 4 (a); (2) Water content increases and close to the plastic limit, the annular water film in soil particles increases and as a network structure, there are strong and weak bound water exist in soil simultaneously ,as shown in Figure 4 (b); (3) Water content reaches the liquid limit, all the voids of soil particles are filled with water, there are strong bound water and abundant weak bound water exist in the soil particles, as shown in Figure 4 (b); (4) Water content beyond the liquid limit, all soil particles completely immersed in water, there are free water in soil, as shown in Figure 4(c).Relevant studies showed that with water content changes, the soil-solid adhesion state is quite different [13]. For the same clay, under different conditions the change of water content can change its adhesion force by 100 times. The adhesion on a solid surface is closely related to the soil water content [14]. Some scholars use quadratic parabola to describe the relationship of soil adhesion and water content, as shown in Figure 5. It can be seen from the figure that when soil water content is located between the liquid limit and the plastic limit, the adhesion is greater, when it is approached to the liquid limit the soil adhesion reaches the maximum.



(a) **(b)** **(c)**

Fig.4 – Water content in soil

If the soil water content is lower than the plastic limit, there is almost no plastic deformation in clay, the contact area is very small. With the water content increases and exceeds the plastic limit, the water film would formed, which causes the meniscus and moisture tension to bind the soil particles and the solid together; If the water content reaches the liquid limit, the plastic deformation of clay would reach the maximum, but if the water content continues to increase and exceeds the liquid limit, the water film becomes too thicker, the viscous force is very small for the viscous force decrease and the adhesion force reduce correspondingly.

Adhesion and the interface pressure

The plastic deformation of clay will increase with the interface pressure and the action time, In general, the greater the interfacial pressure and the longer the action time are, the greater the plastic deformation of clay is. The larger the contact area is, the greater the adhesion force is. If the water content is close to the plastic limit, adhesion would form with the interfacial pressure increases. If the pressure is constant but the time for maintaining the pressure increases, the same result will occur, which is the rheological behaviour of soil.

Adhesion and the particle content

NICHOLS believes that the water content of the maximum adhesive force is directly proportional to the content of soil particles, the relationship between them could be calculated using equation (2) and (3). [15]

$$\omega = 0.186w + 10.10 \quad (2)$$

$$F_a = 0.0044w + 0.48 \quad (3)$$

Where w is the soil particles content; ω is the water content when adhesive force reaches the maximum; F_a is the maximum adhesive force.

The equation (2) and (3) showed that the more the soil particles, the greater the adhesive force, because the large specific surface area of particles will cause high activities. Studies have found that the adhesive force of disturbed soil is about 3 times larger than that of undisturbed soil, and the more disturbed the soil structure is, the greater the adhesion is. [14] Researchers such as Tong Jin and others considered that the particle content is the comprehensive reflection of its mineral composition, the soil with mineral composition Erie and montmorillonite has great adhesion itself [16]. After the soil particles increases, the plastic limit and liquid limit will change, and the plastic index will increase. With the water content range of the initial adhesion and the apparent adhesion enlarged, the amount of sticking and adhesion force increased.

Adhesion and the solid surface conditions

As soil contacts with a solid, the moisture in soil would wet the solid surface, but the wetting speed would be affected by the surface condition. For a hydrophobic solid, the surface is generally small in affinity with water and has poor wettability and low cohesion; but for the hydrophilic solid, it has good wettability and high cohesion. In addition, the solid surface state is also important, for a rough surface the clay particles will wedge into the uneven pits and obviously increase the adhesive force. The rougher the surface is, the easier the adhesion is. Therefore, the soil adhesion is a physical, chemical and mechanical reaction, the higher the soil particles content, the smaller its size, the greater the adhesive force is. For a dynamic process, the roughness and interface pressure of surface are important factors for adhesion.

FIELD TEST AND DISCUSSION

Test profile

In order to further understand the formation mechanism of the bonding layer, a resettlement housing area in southern Jiang Su China was selected as the test site to do the field experiment. Five steel pipe piles were used for the test. The specifications of each pile were shown in Table 1. The purpose of designing different specifications in this experiment is to compare the test results.

Tab. 1 – Parameters of model piles

number	external diameter (mm)	length (mm)	wall thickness (mm)	pile end form	pile body
1	48	1000	3.5	hollow	rough
1	48	1500	3.5	pile tip	rough
1	87	1500	5.5	pile tip	smooth
2	48	1000	3.5	pile tip	rough

In the test, the surface of small-diameter steel pipe pile was covered with burrs densely, as shown in Figure 6, here referred as the rough surface pile; the surface of the large-diameter steel pipe pile was smooth by rinsing, pickling and galvanizing as shown in Figure 7,here referred as the glossy surface pile.

Fig.6 – rough surface

Fig.7 – glossy surface

Fig.8 –The model piles

Fig.9 –The test pile

Tab.2 – Soil parameters of the test site

name	thickness m	water-content ω(%)	unit-weight γ(kN/m^3)	saturation Sr	cohesion C(kPa)	friction angle φ
grey silty clay	1.5	28.1	1.93	94%	26.7	8.5°
tan silty clay	2.5	24.9	1.99	95%	33.6	9.51°

The whole site is formerly farmland with river and ponds, the surface was undulating and dominated by the powdered clay, below the surface is gray and brown yellow powder clay, the soil properties are shown in Table 2.The test area is about 10 m^2, because it was originally cultivated soil and affected by the plant rhizomes at a depth of about 50 cm, after repeated tillage the top plough soil was loose and low in strength, before the test the top soil about 50 cm was excavated. Five piles were pressed into the ground in a uniform and perpendicular speed. The test profile was shown in Figures 8~9.

Test time and sampling

The time of pile driving in this test was mid-10, and the time of pile removal was early-01 next year. According to literature the bearing capacity of jacked pile would reach a stable value after driven into soft clay 72 days [17]. This test met the timeliness requirements of pile bearing capacity. In order to protect the bonding layer of the pile body a digger was used to excavate the soil and piles as a whole, piles were removed from the soil. In the test, a galvanized pipe pile and a hollow steel pipe pile were studied. The Figures 10~12 are the schematic diagrams of test piles.

It can be observed that there was no adhesion on the glossy pile surface, a dense soil block peeled from the pile body directly, which indicated that there was no adhesion between the smooth surface and surrounding soil. But the rough-surfaced pile is firmly adhered a bonding layer which is about 4 to 5 mm in thickness. The formation of bonding layer on pile surface is related to the condition of pile surface, not all piles have the bonding layer.

In order to compare the difference of inter-pile soil and bonding layer and the soil block, three soil samples would be obtained. The sampling position of inter-pile soil was about 20cm below the pile top, removed it with a thin-walled soil collector, the soil sample of the glossy surface pile was taken from the soil block; the soil sample of the rough-surface pile was cut with a blade from the bonding layer, the depth of the three samples was close. Once the soil samples had been taken out, they were immediately placed into a closed container and sealed with a transparent adhesive to prevent water loss, all soil samples were divided into two parts, one used for geotechnical test, the other for microscopic analysis.

Fig.10 –Two test piles

Fig.11 – Soil block from the glossy surface pile

Fig.12 – Bonding layer

Test results and analysis

The soil parameters of three samples are shown in Table 3.

Tab.3 – Parameters of three soil samples

soil samples	plastic limit ω_P(%)	liquid limit ω_L(%)	plastic index I_P	liquid index I_L
inter-pile soil	17.6	34.1	16.5	0.64
rough-surface pile	16.5	34.0	17.5	0.43
glossy-surface pile	14.9	30.1	15.2	0.66

DOI 10.14311/CEJ.2019.03.0031

From the Table 3, it can be seen that the plastic limit, liquid limit, plasticity index and liquidity index of the three samples were all different. According to the geotechnical specifications, the plasticity index mainly depends on the bound water content. The more content it is, the greater the plasticity index, the plastic index of clay is greater than 17.The liquidity index is the degree of soft and hard state. The smaller the liquidity index is, the harder the soil is. In Table 3 the bonding layer has the largest plasticity index and the least liquidity index, due to the increase of fine particles in water film, the soil properties of the bonding layer had changed from the silty clay to cohesive soil. However the soil block peeled from the glossy surface pile was still the silty clay. The following is the analysis of the mechanism of the bonding layer.

Pile-soil adsorption process

Negative charges exist on the surface of soil particles, the strong bound water, weakly bound water and free water around soil particles in sequence, as shown in Figure 13.The binding water formed by soil-water interaction, for the attraction of soil particles to water molecules is closed to1000~2000MPa[18].The strong bound water is a layer of extremely thin hydration film that is adsorbed on the surface of soil particles strongly and loses its free completely; the weak bound water is located farther from the surface of the soil particles and distributed around strong bound water, the degree of orientation and firmness to soil particles is less than the strong bound water, therefore, the weakly bound water has higher viscosity, elasticity and shear capacity, the more weakly bound water content is, the stronger the adsorption is, but the content of the weak bound water is related to the clay particles size, the finer the particles are, the smaller the pores are, the closer the pore water to the soil surface, the easier it is to form a weak bound water, and the stronger the adsorption is. [18]

Some scholars measured the bound water content in clay, studied the limit of strong and weak bound water, they found that when water content is about 0.885 times of its plastic limit, the strong bound water content in clay is the maximum, soil in this state is similar to the solid and has no adsorption; when water content is more than the limit but less than the liquid limit, the strong and weak bound water all exist, the clay has adsorption capacity and the total content of bound water is large in the state; when water content continues to increase and exceeds the liquid limit, there are strong bound water, weak bound water and free water in clay, the soil adsorption capacity will decrease. [19]

The closer the water content to the liquid limit, the more the weakly bound water is, the stronger the adsorption is. In the test, with the tiny cohesive particles accumulating on the pile body, much of weak bound water would be adsorbed which increase the adhesion and stick to more soil particles. After water film in shear zone dissipated, the strength and hardness of soil particles on pile body would increase. For a glossy surface pile, due to the smooth surface, the soil particles in water film are not easy to deposit and adhere to the pile body, they reunite with a soil block and wrapped around the pile; for a rough body pile with coarse surface, some tiny clay particles will fill into the pits during the water film dissipation, with the colloidal particles accumulated, a bonding layer formed around the pile body.

Pile-soil adhesive force

The formation of bonding layer is the result of colloidal particles in water film adhering to the pile body. The water film is very important for soil-pile adhesion, because it offered the initial chemical bonds to cause the adhesion between soil particles and solid, the adhesive force mainly is viscous force of water film and water ring gravity.

The viscous force can be calculated as equation (4)[20]. Assume that the liquid with viscosity
η exists in two parallel disks, the radius of disk is R and can separate them from the initial distance $h_1$to h_2 within time t. The separation force equals to the viscous force of water film.

Where R is the radius of particles; η is the viscosity of water film;h_1,h_2 is the initial distance and separate distance; t is the separate time.

$$F_1 = \frac{3\eta\pi R^4}{4t}\left(\frac{1}{h_1^2}-\frac{1}{h_2^2}\right) \qquad (4)$$

The water ring gravity can be calculated as equation (5)[21].

$$F_2 = \frac{2\pi R\gamma}{1+D/b}(1+\cos\theta) \qquad (5)$$

Where θ is the contact angle between water ring and the pile body; R is the radius of soil particles; D is the thickness of soil particles; γ is the surface tension of water ring; b is the depth of soil particles immersed in water ring.

For a glossy surface pile, as shown in Figure 14 the pile body is smooth, only viscous force exists in pile-soil interface, but for a rough surface pile, as shown in Figure 15, due to the pits of surface, except for viscous force, the water ring gravity has greater impact on adhesion.

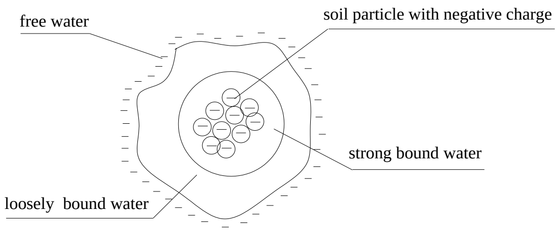


Fig.13–The water state

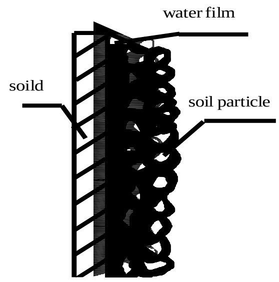


Fig.14–The water film

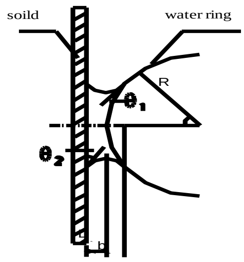


Fig.15– The water ring

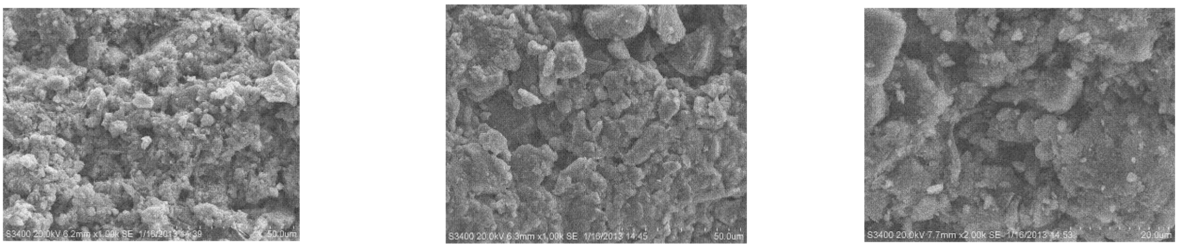
THE MICROSTRUCTURE ANALYSIS

In the process of pile driving, the surrounding soil of pile body would undergo three stages, deformation, strength reduction and destruction, later, it undergoes drainage, particles contact and strength recovery. The essence is the micro-structure change of soil. Therefore, it is necessary to study the soil microscopic characteristics. By comparing the microscopic differences, the essential characteristics can be understood more clearly.

The micro-structure qualitative analysis

Three soil samples were selected in the experiment, including the bonding layer, soil block peeled from the glossy pile and the inter-pile soil. All samples will be frozen and dried. The SEM photos of soil samples are shown in Figure16. It can be seen that the micro-structures of the three samples are obviously different.

DOI 10.14311/CEJ.2019.03.0031



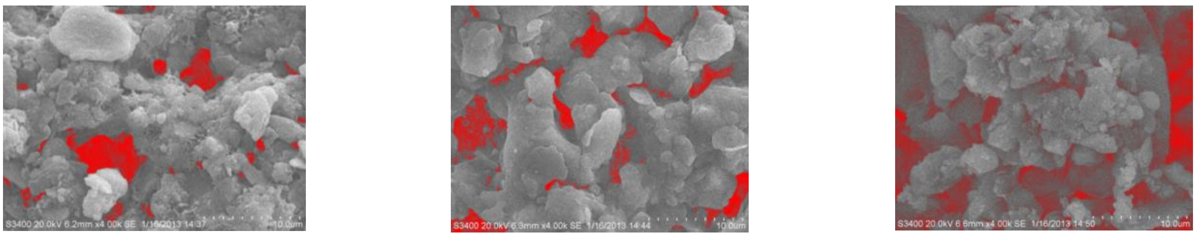
(a) the bonding layer (b) inter-pile soil (c) soil block

Fig.16 – SEM images of samples (4000×)

In the 4000-magnification images, the differences of particles, pores, and agglomerates are very clear. The particles of bonding layer are fine, their connection is dense and accumulating together; the inter-pile soil particles are large and loose, they contact with each other by the way of side-to-surface; the size of particles and pores in soil block is smaller than that of inter-pile soil, their arrangement is tight but uneven, they contact with each other mainly by the way of surface-to-surface.

The micro-structure quantitative analysis

From the SEM images of the three samples, it can be confirmed that the difference of soil micro-structure is mainly reflected the change of soil pore and its connection mode. In order to more clearly compare their micro-structure characteristics, the SEM photographs were processed by professional software, their two-binary segmentation images are obtained, as shown in Figure17.



(a) the bonding layer (b) inter-pile soil (c) the soil block

Fig.17–The processed result of SEM photos

In the processed images, the soil particles of bonding layer are small and dense, clustered into clusters, pores only exist in the aggregates; the skeleton of inter-pile soil is loose, most of soil particles are flakes and there are more pores in it; the particles of soil block are uneven in size, only a part of fine particles accumulate together, the pores mainly distributed in accumulation and large particles, but its skeleton is denser than that of inter-pile soil.

38 soil particle samples were randomly selected from each soil sample. The area, perimeter, equivalent circle diameter, minimum diameter and roundness were measured by image analysis software. Their average value was listed in Table 4. (sample 1 is the bonding layer, sample 2 is the inter-pile soil, sample 3 is the soil block peeled from the glossy surface pile)

Tab.4–The mean size of soil samples

soil sample	area (um²)	perimeter (um)	equivalent circle diameter(um)	the minimum diameter(um)	roundness
Sample 1	1104.13	145.12	35.17	26.11	0.763
Sample 2	2704.47	224.76	56.42	42.92	0.795
Sample 3	2667.95	224.39	54.98	39.21	0.775

In Table 4,the particle area, perimeter, equivalent circle diameter, minimum diameter and roundness of the three samples are obtained, of which the particle size of sample 2 and sample 3 were little difference, however, due to the pile disturbance, the particle size of sample 1 was far less than that of the others, which indicate that the bonding layer is mainly formed by the agglomeration of broken particles, it is the result of condensation of colloidal particles in water film around pile body, the thickness of the bonding layer is related to that of water film in shear zone which further confirms the previous theoretical analysis.

CONCLUSION

An extra bonding layer would form around jacked pile body in soft clay, which enlarges pile superficial area and increases the vertical bearing capacity. This paper mainly studied the formation of bonding layer by theoretical and experimental analysis, the following conclusions are obtained.

(1) During the jacked pile driving into the soft clay, a shear zone would formed near the pile body, later, the concentration of water film in shear zone would change with the dissipation of excess pore water, the tiny colloidal particles would adhere to the pile body, with the excess pore water vanished, the soil in the shear zone would become a plastic body from the plastic flow.

(2) The adhesion between soil and solid surface is an interface phenomenon, which including soil, solid and interface. The main adhesion force is the water ring gravity and viscous resistance. In addition, the adhesion force is related to water content, particles distribution and interface characteristics.

(3) The formation of bonding layer is the common result of pile-soil adsorption and soil adsorption. Coarse surface has the ability to adsorb more colloidal particles, but the adsorption ability of soil particles is related to the weakly bound water because the weakly bound water has higher viscosity, elasticity and shear capacity.

(4) According to the SEM images, it can be obtained that the particles in bonding layer are small and the structure is compact, the inter-pile soil particles are large and has a loose skeleton, the soil block particles peeled from the glossy surface pile are uneven, their pores exist in particles and aggregates. Due to the difference of soil micro-structure is related to the soil particle size, by measurement with the image analysis software, the bonding layer particles are far less than the others, which confirms the previous theoretical analysis.

ACKNOWLEDGEMENTS

The authors wish to thank the National Science Foundation of China (No. 41472283), Jinling Institute of Science and Technology Research Start up Fund (No. jit- rcyj-201402),Construction system science and technology project in Jiangsu province(guidance class No. 2018ZD177)for financial support.

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