Mechanisms of Property Changes of Soft Clays Around Deep Mixing Column

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Abstract: Installation of displacement types of columns such as driven pile, sand compaction pile,lime compaction pile,and deep mixing column causes stress changes in the surrounding soil. The properties will change in surrounding soil. Strength of the surrounding soil will decrease,recover,and increase after column installation. The mechanisms of effects of deep mixing column installation on surrounding clay can be identified into seven categories:disturbance or structure damage of soil surrounding the column due to blade mixing and expansion of admixture injection;thixotropic behaviour of soft clay;soil fracturing around column during mixing and expansion;cement penetration and diffusion from column to surrounding soil through fractures and soil pores;cementation due to increase of cation concentration in pore water;consolidation effect due to increase of effective stress in surrounding soil after excess pore pressure dissipation;heating caused by the chemical reaction of hydration and pozzolanic reaction. These influential factors were investigated through laboratory tests and theoretical analysis. As a result, for soft Ariake clay,test results show that strength due to thixotropic hardening regained completely within 70 days. Theoretical result shows that even in a very low admixture injection pressure,fracturing will occur in surrounding soil.

Introduction

Installation of displacement types of columns such as driven pile, sand compaction pile,lime compaction pile, and deep mixing (DM) columns etc. will cause stress changes in the surrounding soi, Pore pressures in surrounding soil will increase and large displacement and/or surface heave will take place in the surrounding ground.The properties of the surrounding clay will also change and moreover, the undrained shear strength will be decreased during installing, and recovered and increased. The bearing behaviours of the columns are greatly affected by this “set up” in the surrounding clay. Various investigations have been conducted to analyze these kinds of effects experimentally and theoretically. Earliest investigations of this problem were on the effects of pile driving in clays.he mechanisms of effects of pile driving on surrounding clay into four major categories ; remoulding or partial structural alteration of the soil surrounding the pile ; alteration of the stress state in the soil in the vicinity of the pile; dissipation of the excess pore pressure developed around the pile; long-term phenomena of strength regain in the soil. Ref. identified that the surrounding soil fractured during pile driving. He existence of fractures speed up the consolidation process. All of these aspects are available for other installation methods， but the affecting mechanisms are different. For the DM improved soft clay, laboratory and field test results showed that there existed an influence zone of property changes in surrounding clays. This paper analyzes the mechanism of property changes in the sensitive marine clay around DM column through laboratory tests and theoretics.

Ariake Clay Theory

The clay soil used in this study was Ariake clay extracted from a marine deposit on Saga Plain, Japan. Ariake clay is a structured clay. This clay has high sensitivity, low bearing capacity, and it is one of the most problematic soils in Japan. The clay samples were extracted from a depth of 2.0 to 2.5 m.

Frictional sliding crack model is showm in fig.1. This clay soil contains about 60% portion of clay,30% portion of silt, and 10% portion of sand, respectively. The takes the simpler form is:

$$\begin{cases} K_{\mathrm{I}} = \frac{F \sin j}{\sqrt{p\,(l+l^{*})}} - \sqrt{p\,l}[s_{11} \cos^2(q+j) + s_{22} \sin^2(q+j)] \\ K_{\mathrm{II}} = -\frac{F \cos j}{\sqrt{p\,(l+l^{*})}} - \sqrt{p\,l}[\frac{1}{2}(s_{11} - s_{22}) \sin 2(q+j)] \end{cases} \tag{1}$$

$$\begin{cases} K_{\mathrm{I}} = \frac{F \cos q}{\sqrt{p\,l}} - s_{22}\sqrt{p\,l} \\ K_{\mathrm{II}} = -\frac{F \sin q}{\sqrt{p\,l}} \end{cases} \tag{2}$$

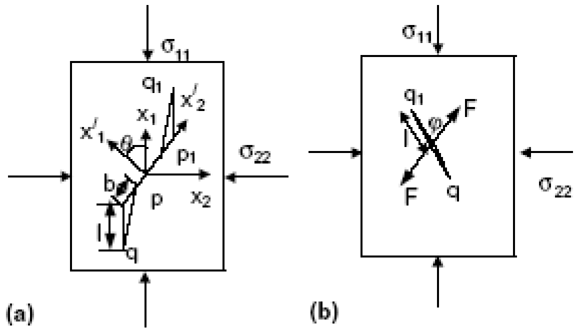

Fig. 1. Frictional sliding crack model with: (a) simplified geometry of tensile wing crack and (b) splitting forces.

The Atterberg limit data of the clay samples are shown, which indicates an average liquid limit of 100%and an average plasticity index of 65%. This soil can be classified as a high plasticity clay soil. The field water content of this soil typically ranges from 90% to150%, which is higher than its liquid limit. The water content of remoulded samples is from 130% to 140%. Specific gravity of this soil Gs is about 2.65. The Ariake clay has a very high sensitivity and its sensitivity is generally around 10,however, in the extreme circumstance with salt leaching.

Laboratory Test Program

In this study, the tests were conducted to investigate the related mechanisms as follows: (1) model column installation to investigate the soil thixotropy, cement penetration, and soil fracturing; (2) soil fracturing observation tests; (3) thixotropic effect tests.

Model Column Installation Test

In order to investigate the mechanisms of properties change of surrounding clay laboratory model column was installed in a model ground by using a small-size soil-cement mixing device. Model ground was created in a concrete soil tank with plan dimensions of 1.5m ×1.5m and a height of 1.0m.Remoulded Ariake clay was consolidated under pressure of about 15 kPa for 6 months. After reconstitution ,average shear strength was about 20. The sensitivity of this clay after consolidation was not so high and ranged from 2 to 3. After reconstitution model columns were installed in the ground to investigate the thixotropic effect, cement penetration, and soil fracturing.

Soil Fracturing Test

Laboratory vane shear test was conducted to investigate the contribution of shearing action of soil fracturing by observing the shape and fracturing range in the clay around the vane wings. In this study, the vane shear device was used to simulate the deep mixing machine. The clay sample was undisturbed Ariake clay extracted from the same site as the remoulded clay sample. The clay sample was set in a plastic container having an of 75 mm, wall thickness of 7 mm, and height of 60 mm, respectively. This vane wing had r of 20 mm and the height of 40mm. The sample container was fixed on a pedestal. After the vane wings were inserted in the soil, the pedestal was forced to rotate at a rate of 3°/min. The development of fractures was observed during the rotation.

Thixotropic Effect

To investigate the thixotropic behavior of the Ariake clay used in this study, a series of tests were performed. The Ariake clay was firstly remoulded and then the remoulded clay sample was re-consolidated by allowing leaching to reduce some part of the electrolyte in one sample. Again the soil sample was completely remoulded and its water content was adjusted to 130%. The remoulded clay was divided and transferred to several containers. The shear strength of the soil in each container was determined using laboratory vane shear test after being rested for prescribed days.

Mechanism Analysis

Soil Disturbance

Since deep mixing columns are constructed through mixing in-situ soft clay with chemical admixtures by using rotating blades, there exist two types of forces acting on the surrounding clay around the column. The first force is created by an expanding action. This expanding action is caused by the injection pressure of chemical admixtures. The second force is created by a shearing action and it results from blade rotation with a shear force. These two effects can generate excess pore water pressures and disturb the surrounding clay so that a plastic zone is form round the column. This disturbance can result in of strength in the surrounding clay. The degree of disturbance depends on the sensitivity of theclay, injection pressure, and the configuration of the. the strength variation of the surrounding soil in this study. From this figure, it can be seen that the strength decreased in the range from column edge to about four times the column the maximum value of about half of its original strength.

Thixotropic Behavior of Ariake Clay

It is well known that a soil specimen after remoulding can lose part or all of its strength due to disturbance and then regain its strength due to thixotropic hardening. Thixotropy is one of the controlling factors for the strength reduction and recovery during and after soil mixing. The degree of thixotropy depends on the type of clay mineral, clay structure, water content, and type and concentration of the ions dissolved in the pore water. The thixotropic effect on the strength reduction and recovery after the installation of columns was investigated in the model column installation study. As shown in the strength reduction and recovery after mixing were different when one was mixed without cement slurry labeled and the other was mixed with cement slurry labeled . As compared between the cases, the with-cement case had a wider range of the clay with reduced strength than that without cement. The inelastic part of the strain increment during the stage of strain-softening can be expressed as following:

$$\begin{pmatrix} de_{11}^{m3} \\ de_{22}^{m3} \end{pmatrix} = \frac{w_0 A\sqrt{pl}}{\sqrt{w\sin(pl/w)}} \begin{pmatrix} \sin 2q \\ -\sin 2q \end{pmatrix} d\tilde{b}_3 + \frac{8w_0 p(1-v_0^2)\tilde{w}\tan\frac{pl}{2w}}{E_0} A^2 \begin{pmatrix} 0 \\ s_{22} \end{pmatrix} d\tilde{l}$$
$$+w_0 \begin{pmatrix} 0 \\ -2\cos q \end{pmatrix} \left(\frac{\sqrt{2w\tan\frac{pl}{2w}}}{\sqrt{pl}} A\tilde{l} d\tilde{b}_3 + \frac{4(1-v_0^2)\sqrt{2\tan\frac{pl}{2w}}}{\sqrt{w\sin\frac{pl}{w}}\,E_0} At_{eff1} d\tilde{l} \right) \quad (3)$$

This is because the cement slurry injection in would extend the fractures developed in the clay. Since there was no chemical agent added in the strength recovery in this case mainly resulted from the thixotropic effect. However, strength recovery in the with-cement case resulted from a combination of the thixotropic effect and cementation. It is shown that significant strength increase occurred near the columnas compared that distant from the column in the with-cement case. For the with-cement case, there strength was completely regained after a 7-day curing period. The clay had about 1.5 times the original shear strength in the close region from the column. For the without-cement case, the soil only returned to 70% of the original shear strength even after being cured for 28 days. The dependence of the complete stress–strain relation on a/w for the doubly periodic rectangular clay is showm in fig.2, and the dependence of the complete stress–strain relation on the crack interface friction coefficient is showm in fig.3.

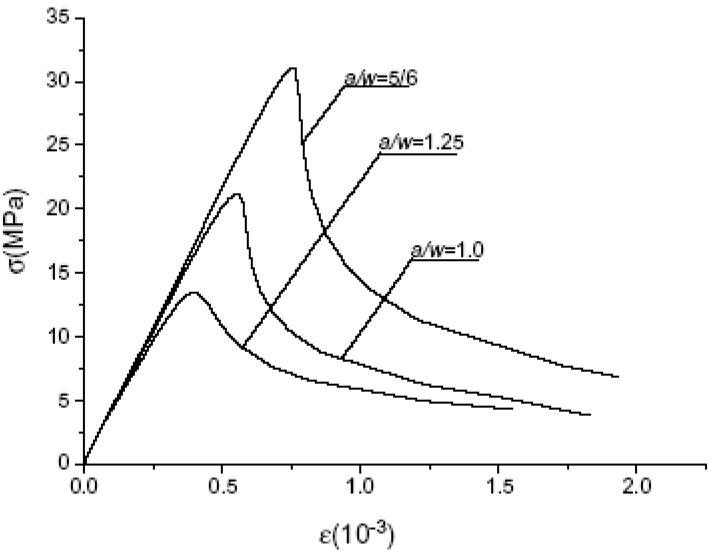

Fig. 2. The dependence of the complete stress–strain relation on a/w for the doubly periodic rectangular clay

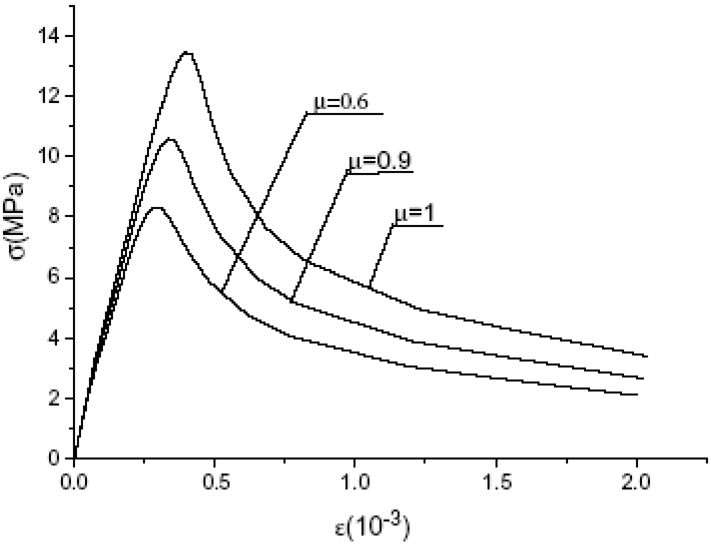

Fig. 3. The dependence of the complete stress–strain relation on the crack interface friction coefficient

The shear strengths of the clay after being completely remoulded and rest for prescribed days were determined using the laboratory vane shear test. the clay after being completely remoulded almost lost all the strength from that of the undisturbed soil. The strength recovery started when the clay was set for rest and the recovery continued for even.

Cement Penetration and Fracturing Phenomenon

Cement penetration into fracture was also investigated in the model column installation. In order to clearly observe the fracturing phenomenon,gypsum slurry was used as the admixture instead of cement-slurry since the gypsum slurry can quickly harden and crystallize. A hole with a diameter of 0.65m and depth of 0.4m was bored near the column with a distance to the column edge of 50mm to control the direction of the main fracture. The hole was filled with lightly compacted sand. The images of this test are shown. Slurry was made with a water-gypsum ratio of 100% and 15% gypsum to dry soil weight. After column was installed, the clay was excavated to investigate the fractures by visually observing crystallized gypsum formed in the surrounding clay, presents an image of the column,sand hole and excavated soft clay. The sand hole was colored in white and hardened by gypsum. It was also found that there existed a white band between the column and the sand hole with a width from 1mm to 2mm. This result indicates that slurry flowed into the sand hole through fractures. The gypsum were also observed around the column in radial directions in a range of about twice the column .Fractures were found to distribute from the top to bottom around the column. Thus,it was clearly confirmed that admixture can penetrate into surrounding soil through fractures. Ref. explained that fractures are filled with two fluids: one from injected slurry to open the fracture,and the other from pore water that in filtrate the fracture. Due to the difference in ion concent ration and pore water pressure between the column and clay,ions in the cement slurry would diffuse into the surrounding clay. Since there exist fractures in the vicinity of the columns after mixing,cement slurry can conveniently fill in the fractures under the expanding force during mixing. The ions in cement slurry can diffuse into the soil mass not only from columns but also from fractures filled with slurry. Ref. reported that the diffusion of lime from lime columns can change the of clay minerals, such as the cation exchange capacity (CEC) of an Indian marine clay. From their laboratory diffusion test,the CEC increased from 35.9meq/(100g) to 45.1 meq/(100g),which is about 30%increase. Lime content and pH also increased.

Cementation

After cement slurry filling the fractures and diffusion, cementation will develop in the surrounding clay. The increase in the electrolyte concent ration would break down the existing clay particle-water system. The excess cations would be attracted and/or adsorpted to the negatively charged clay surface and start equalization of the concent rations. This equalization of the concent ration would be achieved by hydrogen bonding. cationhy dration, attraction by osmosis, dipole orientation in an electric field, and attraction by London dispersion forces. Therefore, more cations are adsorbed into the diffuse double layer of clay particles, and cations may react with the released alumina and/or silica from clay minerals, resulting in aggregation and improving the engineering behaviour of the surrounding clay. Chemical reactions take place in the surrounding clay, which shortens the time of strength regain of the surrounding clay.

Consolidation

Field and laboratory measurements showed that installation of columns induced high excess pore water pressures in the surrounding soil. Ref. found that there was a consolidation process involved in the surrounding soil after installation of DM columns with the dissipation of excess pore water pressures. The existence of fractures in the surrounding soil would accelerate the dissipation of excess pore water pressures. Some of the pore water will flow into fractures driven by high excess pore pressure. This consolidation process can also contribute the strength increase in the surrounding soil. The strength increase due to consolidation after installation of DM columns is similar as that after driving piles into soft clay or installation of sand compaction piles (SCP) in soft clay as studied by Randolph.

Heating

Hydration and pozzolanic reaction can generate heat, which raises the temperature of the column and the surrounding clay. In-situ measurement by Ref. showed that the temperature increased till to 10 to 30days after installation. The maximum increase in soil-cement column was about 40°C.The curing of soil-cement mixture under high temperature resulted high unconfined compressive strength. High temperature can also lead to drying, which results in reduction of water content in the columns and surrounding soil. Consolidation in high temperatures can also speed up the ageing effect of marine clay. This mechanism becomes more significant when quick lime or dry cement power is used than when cement slurry is used.Thelaboratory test results and discussions, the mechanisms of the property changes in the vicinity of deep mixing/mixed column in a short term mainly result from soil fracturing while the property changes in a long term mainly result from thixotropic recovery, consolidation, and cementation.

Conclusions

The mechanisms of effects of deep mixing column installation on surrounding clay can be identified into seven categories: disturbance or structure damage of soil surrounding the column due to blade mixing and expansion of admixture injection; thixotropic behaviour of soft clay; soil fracturing around column during mixing and expansion; cement penetration and diffusion from column to surrounding soil through fractures and soil pores; cementation due to increase of cation concentration in pore water; consolidation effect due to increase of effective stress in surrounding soil after excess pore pressure dissipation; heating caused by the chemical reaction of hydration and pozzolanic reaction. The paper gets some useful results as following:

(1) There are six major factors causing the property changes in surrounding soils during and after installation of columns. These factors are soil thixotrop, soil fracturing, cement penetration and diffusion, cementation, consolidation, and heating.

(2) Soil fracturing will occur in the range of about twice to four times the column diameter. Clay fracturing is the basic factor for property changes and strength increase in surrounding clay. The fractures could provide drainage channels for the injected slurry and induced excess pore pressures. Therefore, in surrounding clay increases much faster than that from diffusion. Consequently, the rate of consolidation and strength regain after construction are increased.

(3) Strength due to thixotropic hardening will regained about 80% within 30 days and will be finished, the property changes in a short term mainly results from soil fracturing while the property changes in a long term is due to thixotropic recovery , consolidation, and cementation.

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