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SOME ASPECTS OF THE SOFT CLAY GROUND IMPROVED WITH CEMENT COLUMNS

QUELQUES ASPECTS DES TERRAINS D'ARGILE TENDRE TRAITE AVEC COLONNES DE CIMENT

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SYNOPSIS: A variety of tests, including the triaxial compression tests and oedometer tests on the soft clay samples installed with mandrels of cement-mixed soil, the laboratory model tests and field loading tests on single cement column or column groups, have been conducted and finite element method has been applied to study the engineering behaviour of the soft clay ground improved with cement columns. Based on the results, the following aspects about this composite ground are discussed: (1) the characteristic of the composite sample with cement-mixed soil; (2) the load distribution between cement columns and the surrounding untreated soil; (3) the bearing capacity; (4) the behaviour of the deformation.

INTRODUCTION

The cement mixing method has often been used to stabilize soft clay ground (Broms, 1990, Terashi et al., 1981). In the method, the soft clay is mixed in situ with cement by a special equipment with rotary mixer head and the cement columns of the same diameter as that of the head are thus installed in the ground. The use of this method in China begins from 1977 and since then a great amount of constructions such as buildings, water tanks and oil tanks etc. have been successfully built on such composite ground (the diameters of the cement columns ranges from 50cm to 70cm). It shows that the method is not only effective to increase the bearing capacity and to decrease the deformation of soft clay ground, but also of economical benefit.

However, many engineering aspects about this composite ground, such as the stress-strain relationship of the cement-mixed soil, the load distribution between cement columns and the surrounding untreated soil, the bearing capacity and deformation behaviour, etc., are still remained to be studied further. The researches on the topics are therefore carried out by the authors (Lin, 1989, Liu, 1991, Xie et al., 1991) and some of the results are summarized in the paper.

CHARACTERISTIC OF COMPOSITE SAMPLE WITH CEMENT-MIXED SOIL

Results From Triaxial Compression Tests

The Ningbo Clay is used in the tests. The cylindrical samples of the clay are 3.91cm in diameter, 8cm high. In the center, the mandrels of the cement-mixed soil, with the diameters of 0.0, 1.46, 1.89, 2.49 and 3.91cm, respectively, and with the cement content, a_w ranging from 10% to 20%, are installed. The composite samples are thus prepared and tested after 3 months.

Fig. 1 shows the relationships between the deviator stress ($\sigma_1 - \sigma_3$) and the axial strain (ε_a) corresponding to 100kPa cell pressure. It can be seen that the stress-strain curves are almost linear at early stage, especially as A_s, the relative column area (i.e. the ratio of the cross sectional area of the mandrel and that of the sample) is greater than 20% and a_w greater than 15%. The stress-strain curves are similar to that of untreated soil when a_w or A_s is small but turn to be strain softening as a_w or A_s is greater. Also can be seen is that the greater the values of A_s and a_w, the more obvious the peak of the curve and the smaller the corresponding strain. These are also true in the cases as cell pressure is greater.

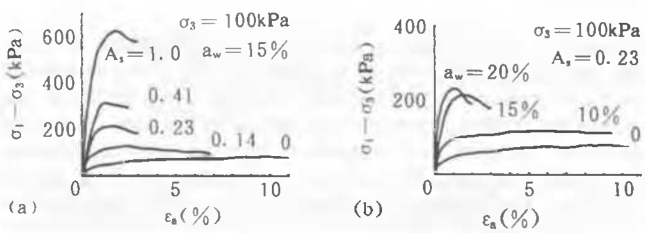

Fig. 1. Stress-strain relationships of the composite samples. (a) A_s varies while $a_w = 15\%$. (b) a_w varies while $A_s = 0.23$.

In addition, the results show that for the samples with the same values of A_s, the undrained shear strength is increased with the increase of a_w and that the magnitude of the increase is greater as a_w ranges from 10% to 15% than as $a_w > 15\%$. This indicates that the optimal cement content is about 15% in practical as the strength is concerned.

Results From Oedometer Tests

e-logp curves

The compression of the samples, as can be seen in Fig. 2, is increased with increasing the vertical pressure P. However, the compression is very small until P exceeds P_y which may be called as the yield pressure. P_y usually increases with increasing a_w and A_s, and may be determined from e-logP curve by the same method as that for determining preconsolidation pressure of clay. The behaviour of the stabilized soil is therefore similar to that of an overconsolidated clay. This may be the one of the reasons why the settlements of most buildings constructed on such composite ground are small.

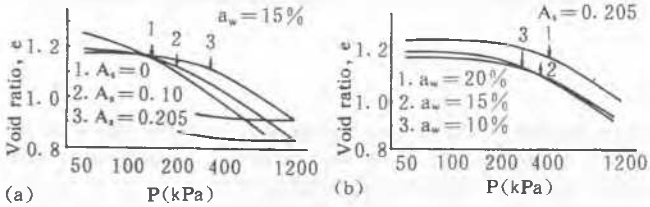

Fig. 2 e-logP curves. (a) A_s varies while $a_w=15\%$. (b) a_w varies while $A_s=0.205$

Composite confined modulus

The composite confined modulus of the improved ground, M_c, is usually calculated as follows:

$$M_c = M_p A_s + (1 - A_s) M_s \qquad (1)$$

in which M_p and M_s are the confined moduli of the cement column and the untreated soil, respectively.

However, the test results show that the relationships between M_c and A_s are not linear as suggested by Eq. 1 but related to vertical pressure P as illustrated by Fig. 3 where M_c' is the composite confined modulus obtained from the tests. It can be seen that $M_c' > M_c$ as P is not very large and that the relative difference between M_c and M_c' is greatest as P is about 200kPa. The composite confined modulus may therefore be underestimated for practical cases if using Eq. 1 and should be calculated as follows to take account of the influence of stress level:

$$M_c = \beta[M_p A_s + (1 - A_s) M_s] \qquad (2)$$

where β is a coefficient related to stress level and may be estimated either from Fig. 3 combined with engineering experience or based on case studies.

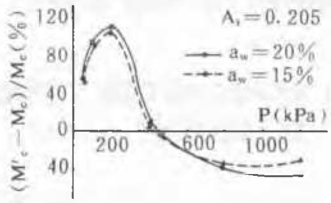

Fig. 3. Variations of the composite confined modulus with vertical pressure, from oedometer tests.

LOAD DISTRIBUTION BETWEEN CEMENT COLUMNS AND SURROUNDING SOIL

Results From Laboratory Model Tests

The load distribution between cement column and the surrounding soil may be expressed by stress ratio, n, which is defined as the ratio of axial stress in cement columns and the vertical stress in the surrounding soil.

Fig. 4 shows the relationships between stress ratio, n and the applied load, P, obtained from the model tests on a single column. As can be seen from the figure, n is increased as P increases at the early stage of loading and then decreased. n also increases with the increase of the column length, L. This means that the stress ratio is related to stress level and the length of column.

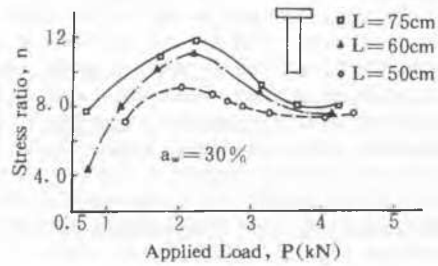

Fig. 4. Relationships between the stress ratio, n and the applied load, P, from laboratory model tests.

It is shown by the model tests on column groups that the stress ratio is also affected by the spacing and the cement content of the columns. The smaller the spacing and the higher the cement content, the greater the stress ratio will be.

Results From Field Loading Tests

Fig. 5 shows the stress ratio measured directly from field loading tests on a single column with loading cap. It can be seen that n increases at first and then decreases with increasing load. This agrees with the results obtained from laboratory model tests, as mentioned above. Therefore, the value of n should be selected according to the foundation pressure in practical. The test results also show that the stress ratio does not varies significantly with time during each loading stage.

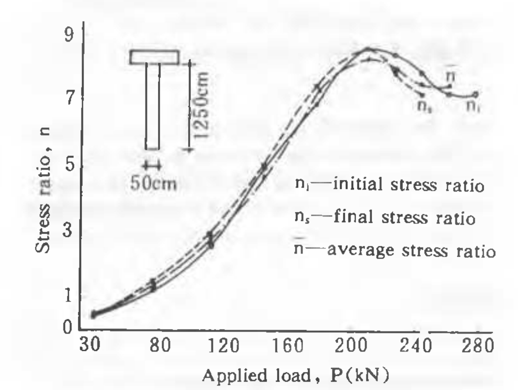

Fig. 5. Relationships between the stress ratio, n and the applied load, P, from field loading tests.

The stress ratio may also be back calculated from observed settlement as follows (Terashi et al., 1981):

$$n = \frac{1}{A_s}(\frac{S_0}{S} - 1) + 1 \quad (3)$$

in which, S_0 and S are, respectively, the settlements of the natural ground and the composite ground.

BEARING CAPACITY

The Influence Factors Of Bearing Capacity

Besides the properties of soil, the main influence factors of the bearing capacity of the composite ground are the cement content, the relative area and the length of columns, etc.. The results from both the laboratory model tests and the field loading tests have shown that the bearing capacity of the composite ground is increased with increasing the cement content, relative area and length of columns. However, only within a certain range, the effects of the column length is significant. If the cement content is high, the effects of column groups should be also taken into consideration.

The Estimate Of The Bearing Capacity

The equation often used in practical engineering for calculating P_f, the ultimate bearing capacity of the composite ground is as follows:

$$P_f = A_s P_{cf} + (1 - A_s) P_{sf} \quad (4)$$

in which, P_{cf} and P_{sf} are the ultimate bearing capacity of the cement column and of the surrounding soil, respectively. Eq. 4 implies that the ultimate bearing capacity of the column and of the surrounding soil are mobilized at the same time. This may be true for flexible columns such as stone and sand columns but not for the cement column since its stiffness is greater, mainly depending on the cement content. In the case that the bearing capacity of cement column is controlled by the strength of the column material, only a little part of the bearing capacity of the surrounding soil is mobilized while the one of the cement column reaches to its ultimate value, owing to the relationships of stress-strain of the cement column and that of the soft clay are different and the strain corresponding to the peak value of strength of the cement column is much smaller than that of soft clay. In addition, some uncertain factors such as inhomogeneity of the columns may also affect the bearing capacity. Therefore, Eq. 4 should be modified as

$$P_f = \alpha A_s P_{cf} + \eta(1 - A_s) P_{sf} \quad (5)$$

where α is a modifying coefficient; η is the coefficient of mobilization of the bearing capacity of surrounding soil assuming that the deformations of the soil and the cement column are compatible.

DEFORMATION BEHAVIOUR

Finite Element Analysis

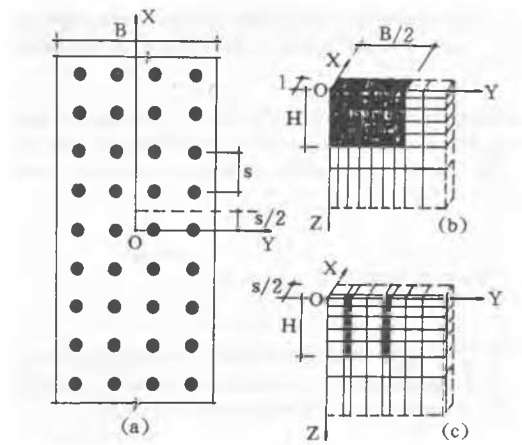

Fig. 6. Finite element analysis scheme. (a) The plan of a composite ground with cement columns. (b) The idealization in Approach 1. (c) The idealization in Approach 2.

Finite element method has been applied to study the deformation behaviour of the composite ground. In the case of plan strain, the ground (Fig. 6(a)) is idealized as two layers system (Fig. 6(b)) in which the cement columns and the surrounding soil are treated as a homogenously stabilized body with composite parameters, or as column groups system (Fig. 6(c)) in which the circular section of the cement column is replaced by a square one of equal area. In the paper, the former is referred to as Approach 1 while the latter as Approach 2.

Results From Approach 1

Fig. 7 shows the influences of the composite elastic modulus of the stabilized body, E_c and the depth of the stabilized soil, H (equal to the column length) on the deformation behaviour of the composite ground, where B is the width of strip load; E_s, the elastic modulus of the soil; S, the maximum settlement of the ground; S_1, the compression of the soil layer below the columns. As can be seen from the figure, the vertical displacement decreases with the increase of the value of E_c/E_s or of the H/B. However, the curves gradually trend horizontally. This indicates that there is an effective value for E_c/E_s (or H/B) and the benefit of using cement columns to decrease the deformation of soft clay ground is no longer significant if the value is exceed.

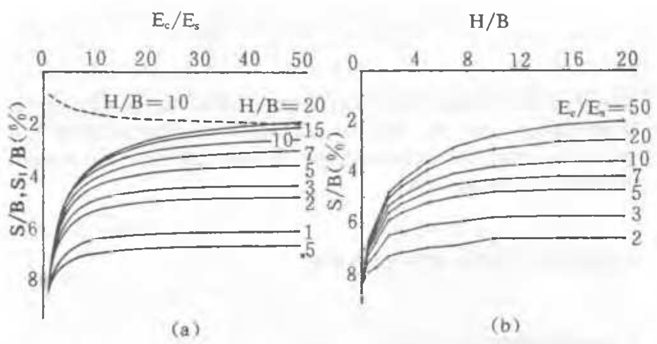

Fig. 7. Deformation behaviour of the composite ground. (a) The influence of E_c. (b) The influence of H.

The relationships between S_1/B and E_c/Es can be seen from the dot curve in Fig. 7(a). The compression of the soil layer under the cement columns is increased with the increase of E_c/E_s.

Results From Approach 2

Approach 2 is applied to investigate the effects of the elastic modulus of cement column, E_p and the relative column area, A_s on the deformation of the composite ground.

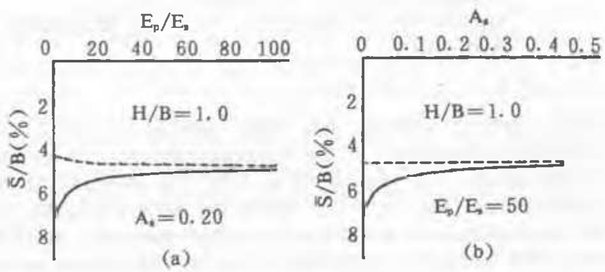

Fig. 8. Deformation behaviour of the composite ground. (a) The influence of E_p. (b) The influence of A_s.

It can be seen from Fig. 8(a) that the average settlement of the ground, $\bar{S}$ decreases with the increases of E_p/E_s, especially as $E_p/E_s<20$. However, as $E_p/E_s>50$, the effect of E_p/E_s seems not significant since the curve approaches to a horizontal line. This confirms the results from Approach 1. Therefore, it may not be economical to allow E_p greater than $50E_s$.

The effects of the relative column area, A_s on the average settlement of the composite ground can be seen in Fig. 8(b). If $A_s \leqslant 0.2$, the settlement is significantly decreased as A_s increases. While $A_s > 0.2$, the effect becomes unimportant.

CONCLUSIONS

The following conclusions may be drawn:

(1) All the results from triaxial compression tests and oedometer tests show that the behaviour of cement-mixed soil is similar to that of overconsolidated clay.

(2) The composite confined modulus of the improved ground is not only related to the relative column area and the cement content but also affected by vertical pressure.

(3) The results from both the laboratory model tests and the field loading tests show that the load distribution between cement columns and the surrounding soil are affected by the relative area, the length and the stiffness of cement columns as well as the stress level.

(4) The results from FEM show that the settlement of the composite ground decreases with the increase of the length, the stiffness and the relative area of the cement columns. However, there exists rational values for both the length and the stiffness of cement columns from economical point of view.

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