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FIELD PROPERTIES AND SETTLEMENT CALCULATION OF SOIL-CEMENT COLUMN IMPROVED SOFT SUBSOIL – A CASE STUDY

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ABSTRACT: The unconfined compression strength, standard penetration test (SPT) results for soil-cement columns and the field loading tests results of the composite subsoil at Lian-Yun-Gang section, Xu – Lian expressway, China, were presented. The methods for calculating the settlement of the soil-cement column improved soft subsoil were discussed. It is recommended that the stiffness of the "slab" on the top of the improved subsoil should be considered in selecting the settlement calculation methods. It is suggested that in the case of a flexible "slab", the *equilibrium method* for the improved layer and the *average stress method* for the underlying unimproved soft layer are preferred, while in the case of a stiff "slab", the *average modulus method* for the improved layer and the *combined method* for the underlying unimproved layer are preferred. Finally, the settlements of the soil-cement column improved subsoil at Lian-Yun-Gang section were evaluated by the suggested methods and compared with the field data. The stress concentration ratio (n) is back-calculated, and it showed that n value increased with the increase of the area replacement ratio.

INTRODUCTION

For highway construction on soft subsoil, controlling of the post-construction settlement is important. For example, in China, the allowable post-construction settlements are 0.3 m for normal section, 0.2 m for box-culvert section and 0.1 m for approach to other structures (i.e. bridge) (Ministry of Transportation, People's Republic of China 1997). There are several methods to reduce the post construction settlement. Improving soft subsoil by soil-cement columns is one of the methods.

Although there are several methods for calculating the settlement of the soil-cement column/soft soil composite subsoil (e. g. Bergado et al. 1994), the conditions that each method is applicable as well as the parameter determination methods still need to be evaluated by the field data. During the construction of Lian-Yun-Gang section, Xu-Lian expressway at eastern China, the field and laboratory tests were performed on the properties of the soft subsoil improved by soil-cement columns and the settlements of the improved subsoil under embankment loading were monitored. These test results and measured field data provide useful information on understanding the deformation characteristics of the soft subsoil improved by the soil-cement column. In this paper, the field conditions and test results are presented. The methods for calculating the settlement of the composite subsoil as well as the parameter determination methods are discussed and evaluated based on the field data.

FIELD CONDITIONS AT LIAN-YU-GANG SECTION

The Lian-Yu-Gang section is about 31 km long and it is divided into 7 subsections and numbered as A1 to A7 (mileage K1 to K31) (Institute of Geotechnical Engineering 2001). The soil profile at the site consists of a weathered crust at the ground surface underlain by an alluvial soft clay layer. Below the soft layer there is a stiff clayey silt layer. The clay particle

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content (<2µm) of the soft clay layer is varied from 56% to 68%. The weathered crust is in an apparent over-consolidated state and the soft clay layer is in a normally consolidated or slightly over-consolidated state. The groundwater level is 1.0 to 3.0 m below the ground surface. The available physical and mechanical properties of the crust and the soft clay layer are summarized in Table 1 (Jing et al. 2001). A typical soil profile at subsection A5 (mileage K19+240 to K22+986) is shown in Fig. 1. The soft clay layer has high compressibility and low strength. Figure 2 shows the typical field vane shear strength (S_u) profiles. For most cases, the S_u values are between 5 to 25 kPa within 10 m in depth.

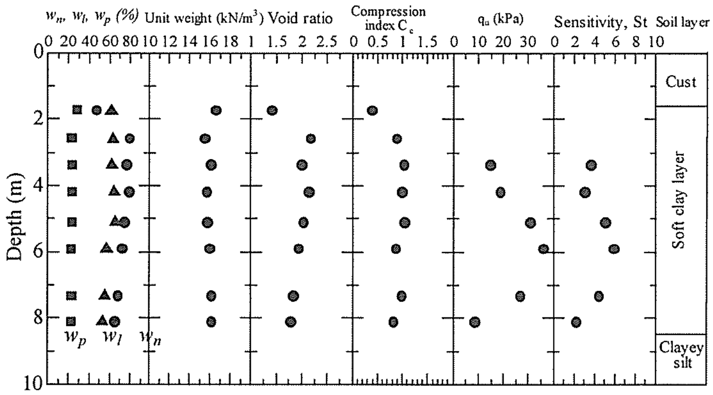


Fig. 1 A typical soil profile at subsection A5

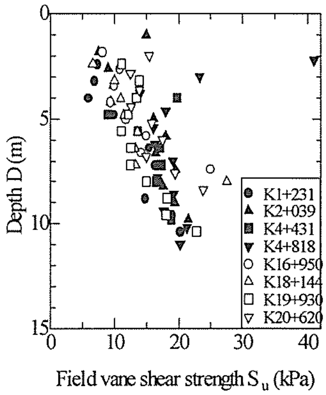


Fig. 2 Field vane shear test results

Table 1 Properties of surface crust and underlain soft clay layer (Jing et al. 2001)

Item	Crust	Soft Clay Layer		
	Ave.	Min.	Max.	Ave.
Thickness (m)	0-4	5.6	13.3	8.4
Water content (%)	34.8	47.4	81.8	69.7
Unit weight (kN/m³)	18.1	15.0	17.4	16.0
Void ratio, e		1.4	2.56	1.92
Liquid limit, W_L (%)	50	21.2	88.2	-
Plasticity index, I_p (%)	20	19.0	50.6	32.2
Compression index, C_c		0.38	1.24	0.84
Coefficient of consolidation, C_v (m²/s)		10^{-8}	10^{-7}	-
Sensitivity, S_t		2.8	9.8	5.5

Table 2 Designed conditions of soil-cement columns

Diameter (m)	Spacing (m)	Pattern	Length	Unconfined compression strength, q_{u28} (MPa)
0.5	1.1 – 1.6	Triangular	Penetrate into the stiff layer 0.5 m	0.8

FIELD PROPERTIES OF THE SOIL-CEMENT COLUMNS

The soil-cement column was used as a main ground improvement method for Lian-Yun-Gang section with a design improving length of about 17 km (more than 50%). Table 2 shows the design conditions of the columns. A 0.3 m thick compacted soil-lime layer was placed at the top of the soil-cement column improved subsoil to form a “slab”. The rate of the lime used was 8% by weight. The soil-cement columns were installed by using a dry mixing method and in most case, the amount of cement used was 59 kg/m.

The field standard penetration tests (SPT) and laboratory unconfined compression tests on the samples taken from the soil-cement columns were conducted to check the quality of the columns. The field full-scale load tests were also carried out for soil-cement/soft soil composite subsoil.

N values of the soil-cement columns

The standard penetration N values for natural subsoil and the soil-cement columns are compared in Fig. 3. Although the improvement is obvious, the increase of N values was different for different subsection. The N values of the columns are about 4 times of those of the natural soil for A3 subsection (mileage K12+510 to K13+914), while about 2 times for A7 subsection (mileage K26+862 to K27+556). At subsection A7, the strength of the natural soil is relatively higher and the improvement effect is less. Generally, the N values of the soil-cement columns are about 15 to 25, and 3 to 10 for the natural soils. The effect of the cement content on N value was also investigated (Fig. 4). Although the data were scattered (partly due to the construction quality control), as a general tendency, the N value increased with the increase of the cement content, especially in subsection A5.

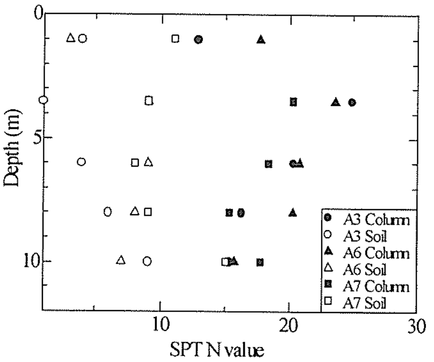


Fig. 3 Comparison of SPT N values

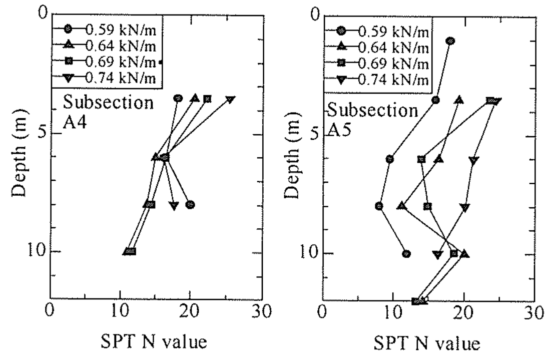


Fig. 4 Effect of cement content on SPT N values

Unconfined compression strength q_u

The q_u values of the soil-cement columns are plotted in Fig. 5. The data are also scattered but for most cases, they were within 0.5 to 1.3 MPa. The q_u values for the natural soft clay layer were in a range of 10 to 40 kPa (refer to Fig. 1). The q_u values of the columns are about 12 to 130 (average 45) times of those of natural soil. The increase of q_u is much higher than that of N values. The diameter of the soil-cement columns was about 0.5 m only, and the influence zone of *SPT* test may be larger than 0.5 m. Also in the field, testing at the exact

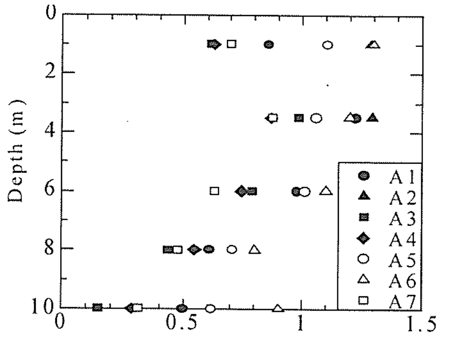


Fig. 5 Unconfined strength of soil-cement column

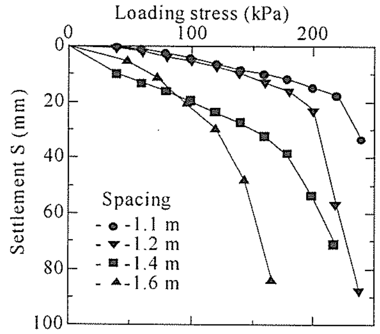


Fig. 6 Load-settlement curves of composite subsoil

center of each column is difficult. Therefore, the field N values may under-estimate the strength of the soil-cement columns. From both Figs. 3 and 5, it can be seen that the strength of the soil-cement columns reduced with depth. The reasons are not clear. It is possibly due to the poor mixing in the deeper zone. These data indicate that in the field, attentions should be paid to improve the quality of the column at deeper zone.

Field loading tests

The field loading tests were conducted for (a) single columns and (b) soil-cement column/soft soil composite subsoil covering with 2 and 3 columns. For a single column, a square shape loading plate with size of 0.5 m × 0.5 m was used. When testing the composite subsoil, the area of the square loading plate was designed to be the same as that of the representative area (column and surrounding soil) of columns. For example, the area of the loading plate for 3 column composite subsoil was 3 times of the representative area of a single column. For spacing of 1.1 to 1.6 m, the area of the loading plate for 3 columns group was 3.14 to 6.65 m^2. The average ultimate bearing capacity of a single column was 240 kN. If ignoring the confine effect of the surrounding soil and converting the bearing load to compression stress (strength) on the column, it was about 1.2 MPa. This value is very close to the maximum q_u value of the laboratory unconfined compression tests. It can be considered that in the case that the column fully penetrated the soft layer and the bearing layer is strong, the bearing capacity failure of the composite subsoil was due to the failure of the column itself. For composite subsoil, the bearing capacity varied from 120 kPa to 300 kPa corresponding to the column spacing of 1.6 m to 1.1 m. The smaller the spacing, the higher the bearing capacity will be. Figure 6 compares the loading-settlement curves of different spacing of 3 column groups with the column length of 8 to 10 m. In the field, the subsoil conditions for different spacing were not exactly the same and a precise comparison is not possible. However, the general tendency of the effect of spacing on loading-settlement curves is clearly demonstrated.

SETTLEMENT OF SOFT GROUND IMPROVED BY SOIL-CEMENT COLUMN

As shown in Fig. 7, the settlement of the soft subsoil improved by soil-cement column consists of two parts, the compression of the composite layer (h_1) and the compression of the unimproved layer beneath the composite layer (Δh_2). For calculating Δh_1, normally a one-dimensional (1D) condition (unit cell) is assumed, and there are two approaches, namely equilibrium approach and average modulus approach. On one hand, 1D assumption ignores the stress spreading effect with depth and thus it tends to over-predict the settlement. On the other hand, it ignores the lateral deformation and tends to under-predict the settlement. These two opposite effects may reduce the error to some extent for 1D settlement calculation. The lateral displacement depends on the stress level in the soft layer. The higher the stress level, the lager the lateral displacement will be. When considering the lateral displacement, two-dimensional numerical analysis is required.

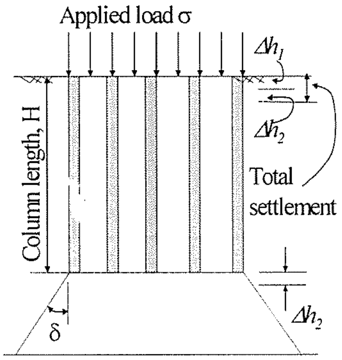


Fig. 7 Model for calculating the settlement of composite subsoil

For the equilibrium approach, Δh_1 is calculated as follow:

$$\Delta h_1 = \frac{(\mu_c \sigma)H}{D_c} \qquad (1) \qquad\qquad \mu_c = \frac{1}{1+(n-1)\alpha_p} \qquad (2)$$

In case of using the compression index, C_c, Eq. (1) becomes:

$$\Delta h_1 = H\frac{C_c}{1+e_{vo}}\log(1+\frac{\mu_c\sigma}{\sigma_{vo}}) \quad (3) \qquad \Delta h_1 = \frac{\sigma H}{D_p\alpha_p + (1-\alpha_p)D_c} \quad (4) \qquad R = \frac{(\Delta h_1)_{eq}}{(\Delta h_1)_{av}} = \frac{(m-1)\alpha_p + 1}{(n-1)\alpha_p + 1} \quad (5)$$

where D_c is constrained modulus of soil, σ is applied average loading on the composite subsoil, H is thickness of the composite layer, α_p is area replacing ratio of the soil-cement column, e_o is initial void ratio, σ_{vo} is initial effective vertical stress in the ground, and n is stress concentration ratio ($n = \sigma_p / \sigma_c$,σ_p is stress on the column and σ_c is stress on the surrounding soil). The value of n is a function of the relative stiffness of the soil-cement column and the surrounding soil, the stiffness and the thickness of the "slab" on the top of the composite subsoil, the degree of penetration of the column into the soft layer, and the area replacing ratio.

For the average modulus approach, the Δh_1 can be calculated by Eq. (4), where D_p is constrained modulus of the soil-cement column, and the other parameters are as defined previously. If the stress concentration ratio is the same as the ratio of modulus (m) of the soil-cement column and the surrounding soil, the above two approaches is the same. Let's define $m = D_p / D_c$, the ratio (R) of the settlements calculated by the equilibrium method, $(\Delta h_1)_{eq}$, and the average modulus method, $(\Delta h_1)_{av}$, can be expressed by Eq. (5).

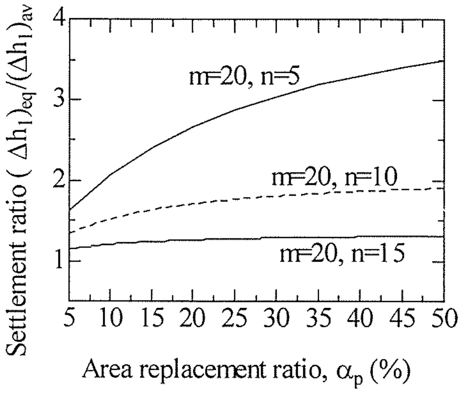


Fig. 8 Settlement ratio versus area replacement ratio

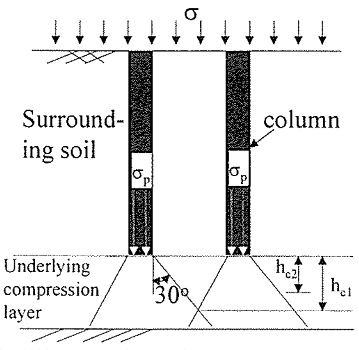


Fig. 9 Illustrating the stress spreading under a column

As shown in Fig. 8, the R is a function of m, n and area replacement ratio (Δ_p). When m is larger than n, the R is larger than 1. There are two reasons for $m>n$: (1) due to the lower stiffness of the "slab" (or soil layer) on the top of the soil-cement column improved composite subsoil, the settlement of the column and the surrounding soil may be different, which tends to reduce the stress concentration on the column and (2) there is penetration of the column into underlying soil layer, especially for the case that the column partially penetrated into the soft subsoil, which tends to reduce n value also. Another point is that the equilibrium method is mainly considering the settlement of the surrounding soil and the average modulus method is assuming that the settlement of the surrounding soil and the columns is the same.

For the settlement of the underlying soil layer (Δh_2), also two approaches are available. One is considering the soil-cement column improved zone as a block and the load is uniformly transferred to the underlying layer (Bergado et al. 1994). Then the compression of the underlying layer can be calculated by using the conventional method. This method ignores the penetration of individual column into the underlying layer. In the later discussion, this method will be referred as average stress method. Another approach considers that the main load to the underlying soil is from the columns and the load is spread from the edge of the column as illustrated in Fig. 9 (Technical Center for Land Development, Japan 1999). This approach can indirectly and partially consider the penetration of the column into the underlying soil. The approach will be called as concentrated stress method. The stress spreading angle, δ, is normally assumed as 30^o (estimated as $\delta = 45^o - \phi'/2$, $\phi' = 30^o$).

For the average stress method, the stress spreads in plane strain condition, and for the concentrated stress method, the stress spreads in three-dimensional (3D) and reduces faster with depth. Therefore, when the underlying layer is thin, the concentrated stress method will yield a lager settlement, but for a thick underlying soft layer, the average stress method may give a larger settlement. For the concentrated stress method, at a certain depth of h_{c1} from the tip of the column, the stress spread from each column starts to influence each other. Using a stress-spreading angle of 30^o, h_{c1} can be calculated as follows:

$$h_{c1} = \frac{(D_e - d)\sqrt{3}}{2} \qquad (6) \qquad\qquad h_{c2} = \frac{d\sqrt{3}}{2}\left(\sqrt{\frac{n}{(n-1)\alpha_p + 1}} - 1\right) \qquad (7)$$

where D_e is the equivalent diameter of the influence zone of a column (or unit cell diameter) and d is the diameter of a column. Another factor is that when the stress concentration ratio (n) is low, the stress spread from the column at the depth of h_{c1} from the tip of the column is less than the applied average stress. A depth (h_{c2}) at which the spread stress from the column (δ=30^o) is the same as the applied average stress can be expressed by Eq. (7).

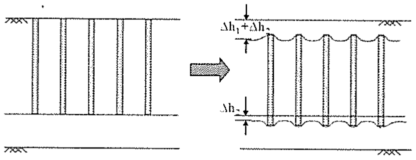
For example, when n=10, d=0.5 m, and the spacing S=1.6 m (triangular pattern), h_{c1}=1.02 m and h_{c2}=0.59 m. The difference between h_{c1} and h_{c2} reduces with the increase of the n value and the area replacement ratio (α_p). It is proposed that in settlement calculation when needs to consider the penetration of the column into underlying soil, the concentrated stress method can only be used within h_{c2}, and below it using the average stress method. This combines the average stress method with the concentrated stress method will be referred as combined method.

For h_{c2} of 0.6 m, the diameter of the column of 0.5 m, the applied average stress of 100 kPa, and with the soil properties of compression index (C_c) of 0.8, initial void ratio of 2 and initial vertical effective stress of 50 kPa, the calculated compression of this 0.6 m thick layer are 75 mm and 115 mm based on the average stress method and the concentration stress method, respectively. In other words, about 40 mm column penetration is evaluated. The penetration depth will increase with the increase of the stress concentration ratio. In the field, the penetration of the column strongly depends on the stress level under the column and eventually the applied stress intensity. Also when shear failure occurs under the column, the penetration will increase rapidly. Conceptually, the method proposed here is for the cases where the stress under the column is less than the ultimate bearing capacity of the soil.

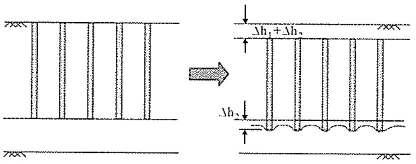
Up to this point, a question of which method needs to be used for calculating the settlement of a soil-cement column improved subsoil has to be answered. As shown in Fig. 10, in case of a flexible "slab" on the top of the improved subsoil, it is suggested that the settlement calculation needs to focus on the settlement of the surrounding soil, i.e. for the improved zone using the equilibrium method and for the underlying soft soil using the average stress method (Fig. 10 (a)). For the system with a stiff "slab", using the average modulus method for the improved zone and the combined method for the underlain soft soil (Fig. 10 (b)).

COMPARING THE CALCULATED SETTLEMENT WITH THE FIELD MEASUREMENT

Considering the average thickness of the subsoil at Lian-Yun-Gang section, a cross-section of the embankment on the soil-cement column improved composite subsoil was assumed as in Fig. 11. In settlement calculation, referring the field conditions, it was further assumed that the spacing between columns varies from 1.1 to 1.6 m, and three embankment heights of 2.5, 3.5 and 4.5 m were considered. Since the "slab" on the ground was only a 0.3 m thick lime improved soil layer, we considered it as a flexible "slab" case. The unit weight of the embankment was assumed as 18 kN/m^3. The other conditions are given in Fig. 11. The calculated values and the field measurements (Institute of Geotechnical Engineering, 2001) are compared in Fig. 12. It is worth to mention that in the field, the thickness of the soft subsoil is varied and which is the main reason for the scatter of the field data.



(a) Flexible "slab" case



(b) Stiff "slab" case

Fig. 10 Deformation pattern of improved subsoil

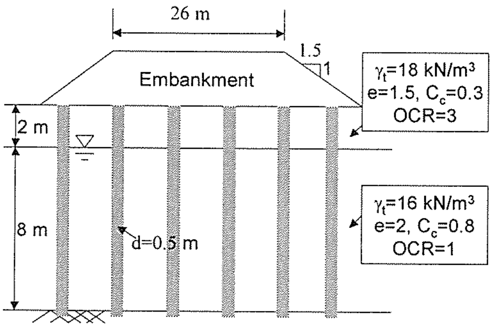


Fig. 11 Assumed settlement calculation conditions

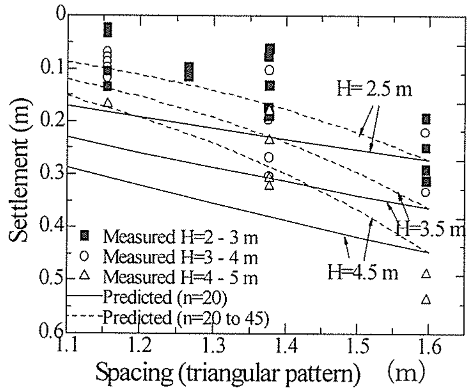


Fig. 12 Comparison of calculated values with Measurements

Table 3 Relation between n value and spacing

Spacing (m)	1.1	1.2	1.3	1.4	1.5	1.6
n	45	40	35	30	25	20

Regarding to the stress concentration ratio (n), Shen et al. (2001) measured the n value by laboratory model tests for soil-cement column partially penetrated into the soft layer case and a value of 5 to 15 was obtained. In Lian-Yun-Gang section, the columns fully penetrated into the soft layer, and n value of larger than 15 can be roughly estimated. As discussed previous that n values are generally less than the modulus ratio of m. One of the methods for estimating the modulus of the soil-cement column is to relate the modulus with the unconfined compression strength q_u (Kitazume 1996). If using this method, the modulus ratio will be the same as the unconfined strength ratio. For Lian-Yun-Gang section, the average value of unconfined strength ratio of the soil-cement column and the surrounding soil was about 45. Therefore, as the first approach, a constant n value of 20 was considered. It can be seen that the calculation over predicted the settlement of smaller spacing cases. Under a flexible "slab" condition, increasing the α_p value tends to increase the arching effect between columns and reduce the stress on the surrounding soil and resulting in a higher stress concentration ratio. Also, the increasing of the α_p value implies the smaller the settlement of the composite subsoil, the less the hardening (less modulus increment) of the soft soil surrounding the column. This phenomenon also contributes to the increase of n value with the increase of α_p. Then a case considering the n value varies with spacing (S) (Table 3) was conducted. The value 45 was the same as the average modulus ratio. The calculated results are closer to the measured data. These back evaluated values seem in contradiction with the results reported by Shen et al. (2001), in which the n values reduced with the increase of the area replacement ratio (α_p). The results obtained by Shen et al. was under the condition of partially penetration and a very stiff "slab", which is different from the conditions considered here. Also, Probaha et al. (2001) reported some triaxial test data on fly ash stabilized column and soft soil composite samples under fully penetrated condition, in which the n values were increased with the increase of a_p values.

CONCLUTIONS

The properties of soil-cement column and the methods for settlement calculation of the composite subsoil were investigated by using the field data from Lian-Yu-Gang section, Xiu–Lian expressway, China. The main results can be summarized as follows.

1) The results of laboratory unconfined compression tests and the field standard penetration tests (SPT) show that cement mixing by dry method is effective in improving the strength and stiffness of the soft subsoil. However, for the case investigated with a column diameter of 0.5 m, the field SPT may not a suitable method to study the properties of the soil-cement column. The field-loading test results for composite subsoil are also reported

2) It is recommended that the settlement calculation methods for the soil-cement column improved subsoil be selected based on the stiffness of the "slab" on the top of the improved subsoil.

- In the case of a flexible "slab", use the equilibrium method for the improved layer (consider the settlement of surrounding soil) and the average stress method for the underlying unimproved layer.
- In the case of a stiff "slab", use the average modulus method for the improved layer and the combined method (combine the average stress method with the concentrated stress method) for underlying unimproved layer.

3) The settlements of the soil-cement column improved subsoil at Lian-Yu-Gang section were evaluated by the suggested methods and compared with the field data. The back-calculated values of the stress concentration ratio (n) increased with the increase of the area replacement ratio.

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