Estimation of settlement of in-situ improved ground using shallow stabilization and floating-type columns

Evaluation de la consolidation des sols améliorés in-situ utilisant une stabilisation superficielle et des colonnes type flottante

R. Ishikura

Yamaguchi University, Japan

H. Ochiai

Kyushu University, Japan

H. Matsui

Taisei corporation

ABSTRACT

The use of shallow stabilization and floating-type cement-treated columns has been developed as a method with acceptable settlement for maintaining the proper functioning of high standard roads or high embankments on soft grounds. So it is most important to predict the total settlement for this type of improved ground. In this study, Consolidation and deformation properties of this type of improved grounds were clarified by the field observation results obtained from two types of full scale test embankments. Further, a method for predicting the total settlement for this type of improved ground with respect to the improvement ratio and depth is proposed. Its validity is confirmed from the field observation results of the improved grounds.

RÉSUMÉ

La stabilisation superficielle et les colonnes type flottante traitées au ciment ont été développées en respectant les normes de consolidation pour les structures de route ou des endiguements sur sols mous. Il est donc essentiel de prévoir la consolidation totale de ce type de sols améliorés. Dans cette étude, les propriétés de consolidation et de déformation ont été clarifiées grâce aux résultats d'observation sur deux expériences d'endiguement réalisées en grandeur nature. Par ailleurs, une méthode permettant de prévoir la consolidation totale de ce type de sol amélioré, tenant compte du coefficient d'amélioration et de la profondeur, a été proposée. La validité de cette dernière a été vérifiée à partir des résultats d'observation des sols améliorés.

Keywords: ground improvement, field observation, floating-type cement-treated columns, stress distribution ratio

1 INTRODUCTION

A technique that combines ground improvements methods such as deep mixing and surface stabilization has been developed. This technique enables the efficient construction of high standard roads or high embankments on a deep soft soil layer. Floating-type deep mixing soil stabilization is a method with acceptable settlement for maintaining the proper functioning of high standard roads or high embankments on soft grounds. The advantage of this method is that it reduces the cost of construction of soil structures on deep soft soil layers. In addition, the soft soil layers are retained under the improved portion; this ensures a smooth flow of ground water in this type of improved ground, which is not the case in ground improvement by the end-bearing-type stabilization method.

In order to establish this method of ground improvement, it is important to predict the settlement of the improved ground with respect to the improvement ratio and improvement depth.

A method for predicting the total settlement for this type of improved ground has been previously proposed, and several loading model tests were conducted (Ishikura et al., 2007). The characteristic of this method is that it can be related to the consolidation layer and improvement parameters such as improvement ratio and improvement depth. In this study, its validity is confirmed from the field measurements in full scale test embankments.

2 TENDENCY OF SETTLEMENT OF IN-SITU IMPROVED GROUND

Two types of test embankments were constructed in order to investigate the tendency of the settlement for a floating-type improved ground with shallow stabilization (Miki et al., 2004). The outline of execution cases is shown in Figure 1. As shown in this figure, the depth of the improved portion was around 8m, and it had different thicknesses of surface stabilization and floating-type deep mixing soil stabilization under low improvement ratio.

Deep mixing columns were arranged uniformly in a rectangular pattern just under the test embankment. In order to examine the consolidation properties of the improved grounds, settlement gauges were installed to the several layers with fixed depth under the center of test embankment.

Figure 2 shows the settlement just below the center of the test embankment. As shown in this figure, soft clay between the improved columns was confined to the upper part of the improved portion in both cases; in other words, compressions of these parts were extremely small. In the lower part of the improved portion, consolidation gradually became dominant.

It was clarified that the layer of the improved portion is distinguished from the confining portion and consolidation layer in proportion to the improvement parameters.

In order to estimate the total settlement for this improved ground, it is most important to determine the thickness of the consolidation layer in relation to the improvement parameters such as improvement ratio and improvement depth.

3 ESTIMATION METHOD FOR PREDICTING THE TOTAL SETTLEMENT OF THE IMPROVED GROUND

In this chapter, the estimation method for predicting the total settlement of this type of improved ground is proposed. First, the homogenized material parameter of the improved portion is estimated with a consideration for the stress distribution ratio. Second, the relation between the consolidation layer and improvement parameters such as improvement ratio and improvement depth is discussed.

doi:10.3233/978-1-60750-031-5-2394

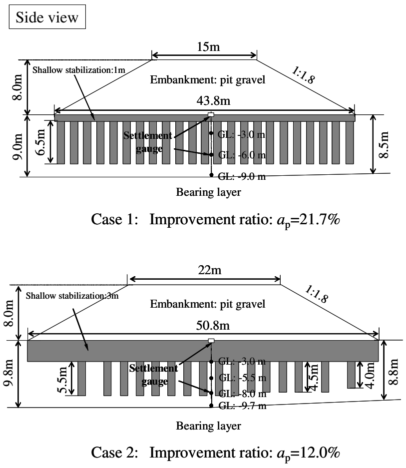

Figure 1. Outline of execution cases.

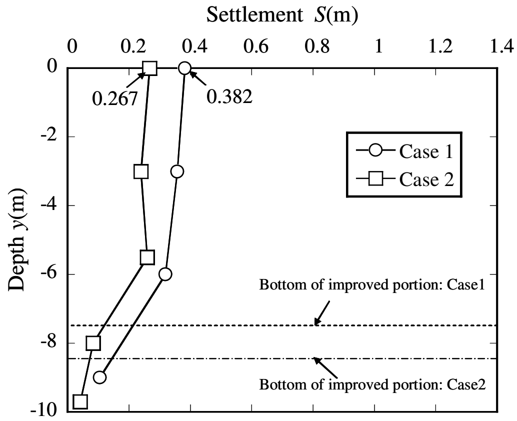

Figure 2. Settlement just below the center of test embankment.

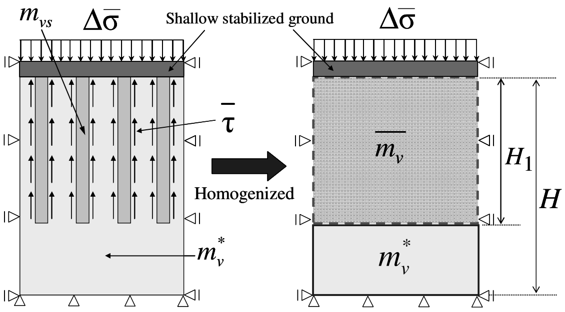

Figure 3. Concept of the homogenized composite ground.

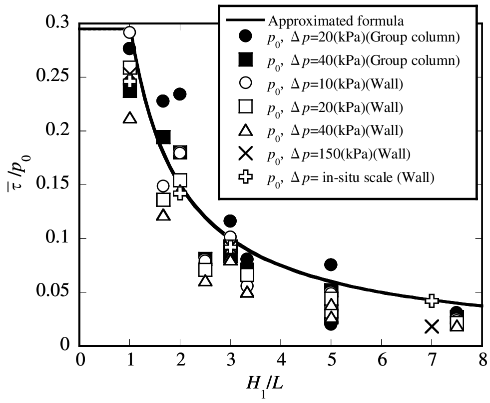

Figure 4. Formulation of upward skin friction.

3.1 *Homogenized material parameters of composite ground*

In order to evaluate the homogenized material parameters of the improved portion using the soil parameters of the improved column and soft clay, an estimation method for predicting the material parameter for composite ground is used (Omine and Ochiai, 1992). Figure 3 shows the concept of the homogenized composite ground. For evaluating stress distribution in the composite ground, stress distribution ratio $\bar{n}$, which is defined as the average ratio between the stress on the improved column $\overline{\sigma_s}$ and on soft clay $\overline{\sigma_*}$, is introduced in Eq. (1).

$$\bar{n} = \frac{\overline{\sigma_s}}{\overline{\sigma_*}} \tag{1}$$

The coefficient of volume compressibility of the composite ground is expressed as follows:

$$\overline{m_v} = \frac{a_p \bar{n} m_{vs} + (1 - a_p) m_v^*}{(\bar{n} - 1) a_p + 1} \tag{2}$$

Here, a_p is the improvement ratio, and m_{vs} and m_v^* denote the coefficients of volume compressibility of the improved column and soft clay, respectively. In order to estimate the value of $\overline{m_v}$, it is important to evaluate the value of $\bar{n}$. This value varies with difference in the improvement parameters.

3.2 *Stress distribution ratio with estimated by skin friction*

In order to evaluate stress distribution ratio $\bar{n}$, it is most important to formulate the skin friction applied around the surface of floating-type columns. FEM analysis with the Cam-clay model as the constitutive equation was performed using axi-symmetric and plane strain models (Ishikura et al., 2006). H, H_1 and L denote the ground depth, the improvement depth and the distance between the improved columns or walls, respectively. The ground surface was deformed equally by the rigid plate on the assumption of shallow stabilized ground.

Figure 4 shows the relationship between the upward skin friction applied around the surface of the improved column and the distance between the improved columns. p_0 denotes the pre-consolidation pressure of the soft clay. $\bar{\tau}$ denotes the average skin friction applied around the surface of the improved column. This value is obtained from the difference between the stress applied on and immediately below the improved column. Each value of $\bar{\tau}$ is normalized by the pre-consolidation pressure p_0. H_1 is normalized by the value of L. As shown in this figure, the normalized average friction $\bar{\tau}/p_0$ decreases with an increase in H_1/L. Furthermore, the maximum value of $\bar{\tau}/p_0$ is almost equal to the shear strength ratio c_u/p_0. The same relationship of in-situ scale condition also shows the same tendency shown in this figure. It is clarified that $\bar{\tau}$ changes under several conditions with different values of H, H_1, and L.

In this study, the value of $\bar{\tau}/p_0$ is determined using the approximate formula given in Eq. (3).

$$\frac{\bar{\tau}}{p_0} = \frac{c_u}{p_0} \cdot \frac{1}{H_1/L} \quad (\bar{\tau} \leqq c_u) \tag{3}$$

Here, c_u is the undrained shear strength. The approximate curve almost corresponds to the relationship between the upward average skin friction and the improvement parameters. By using the average friction $\bar{\tau}$ in Eq. (3), the average stress distribution ratio $\bar{n}$ of the improved portion in Eq. (1) is rewritten in Eq. (4) under the assumption that the ground surface is deformed equally by the shallow stabilized ground.

$$\bar{n} = \frac{(D+1)\bar{\sigma} + \dfrac{\bar{\tau} A_s}{2A_0 a_p}}{(\dfrac{D}{R}+1)\ \bar{\sigma} - \dfrac{\bar{\tau} A_s}{2A_0(1-a_p)}} \tag{4}$$

$\bar{\sigma}$ is the average vertical stress on the improved area. A_0 is the total area of the improved ground, and A_s is the total surface area of the improved columns. D is the depth ratio $H_1/(H-H_1)$,

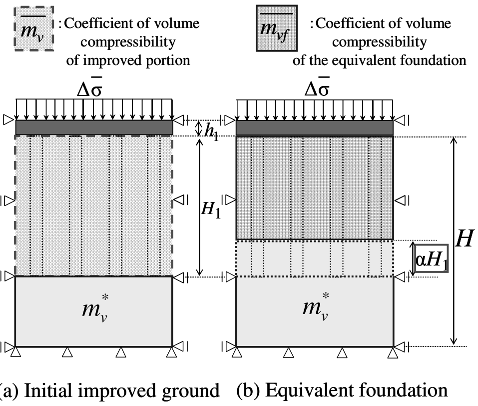

Figure 5. Concept of equivalent conversion ratio α .

Table 1. Parameters used for calculating α .

$\overline{m}_v$	Eq.(2)← $\overline{n}$:Eq.(4)← $\overline{\tau}$:Eq.(3), Improved conditions (a_p, H_1)
$\overline{m}_{vf}$	Eq.(2) ← $\overline{n}=n_f=m_v^*/m_{vs}$
m_v^*	e — $\log p$ relationship
m_{vs}	Inverse of deformation modulus E

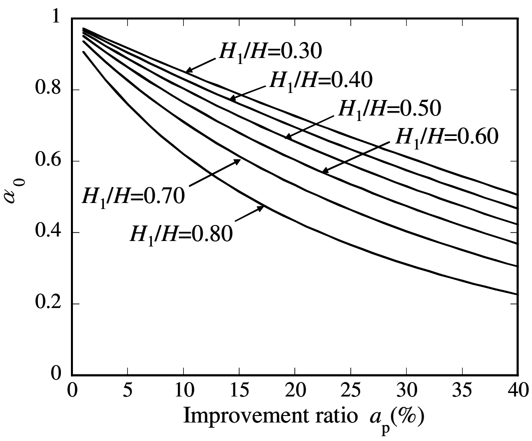

Figure 6. Effects of the improvement parameters (R=100).

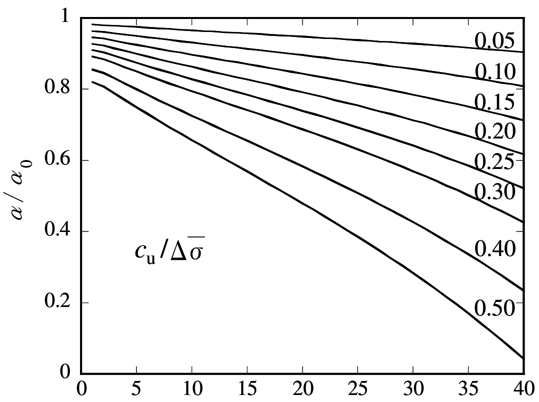

Figure 7. Effects of soil characteristic and loading condition.

and R means the rigidity ratio m_v^*/m_{vs} . By substituting Eq. (4) in Eq. (2), the coefficient of volume compressibility of the improved portion $\overline{m}_v$ is obtained.

3.3 *Determination of thickness of the consolidation layer*

The thickness of the consolidation layer in relation to the improvement parameters in this type of improved ground is determined by using $\overline{m}_v$.

Figure 5 shows the relationship between the consolidation layer and the improvement parameters. As shown in Figure 5(a), when an average vertical stress $\Delta\overline{\sigma}$ is applied on the improved portion that has an average compressibility $\overline{m}_v$ and improvement depth H_1 , the compression of the improved portion is expressed in Eq. (5) as follows:

$$\Delta S_{(a)} = \overline{m}_v H_1 \Delta\overline{\sigma} \tag{5}$$

On the other hand, in Figure 5(b), the improved portion depth H_1 is divided into two parts: a confining portion and an unimproved portion. When the equivalent conversion ratio α is defined as the ratio of the divided unimproved portion thickness to H_1 , the compression of the improved portion is expressed as follows:

$$\Delta S_{(b)} = \overline{m}_{vf}(1-\alpha)H_1\Delta\overline{\sigma} + m_v^*\alpha H_1\Delta\overline{\sigma} \tag{6}$$

The confining portion is defined as the equivalent foundation. In relation to the improvement parameters $\overline{m}_{vf}$ denotes the coefficient of volume compressibility of the equivalent foundation. The value of $\overline{m}_{vf}$ is obtained by substituting the rigidity ratio between an improved column and the soft clay $n_f = m_v^*/m_{vs}$ in Eq. (2). This value of α is expressed in Eq. (7) under the assumption that $\Delta S_{(a)}$ is equal to $\Delta S_{(b)}$.

$$\alpha = \frac{\overline{m}_v - \overline{m}_{vf}}{m_v^* - \overline{m}_{vf}} \tag{7}$$

Table 1 shows the parameters used for calculating the equivalent conversion ratio α . α denotes the function of general parameters such as soil properties, improvement parameters, and skin friction. As shown in this table, α can be obtained for predicting the value of $\overline{m}_v$ corresponding to the stress distribution ratio $\overline{n}$. In order to estimate the total settlement of the improved ground, it is important to determine the value of α .It is necessary that the characteristics of α are clarified by examining the effects of various parameters on α .

Figure 6 shows the relationship between the equivalent conversion ratio α_0 and the improvement parameters with no consideration for upward skin friction under the condition that radius of the improved column is 0.5m. α_0 decreases with an increase in the improvement parameters such as improvement ratio and improvement depth. It is recognized that the rigidity ratio $R = m_v^*/m_{vs}$ has little influence on α_0 when R is over 50.

Figure 7 shows the effects of soil characteristic and load condition on the equivalent conversion ratio α .The value of α is normalized by that of α_0 . α/α_0 decreases with an increase in $c_u/\Delta\overline{\sigma}$. The value of α with a consideration for the skin friction of a floating-type column is obtained from α in Figure 6 multiplied by α/α_0 in Figure 7 in the same improvement ratio.

3.4 *Calculation of settlement of the improved ground*

Figure 8 shows the concept for estimation of the total settlement of this improved ground. In this proposed model, the total settlement is calculated by the summation of one-dimensional consolidation settlements of two layers comprising the equivalent foundation and consolidation layer. Several thicknesses of layers are determined using an equivalent conversion ratio in relation to the improvement parameters such as improvement ratio and improvement depth.

When the equivalent conversion ratio α is determined in relation to the improvement parameters, the compression of the equivalent foundation is calculated by Eq. (8).

$$S_f = \{m_{vs}h_1 + \overline{m}_{vf}(1-\alpha)H_1\}\Delta\overline{\sigma} \tag{8}$$

Here, m_{vs} and $\overline{m}_{vf}$ denote the coefficient of volume compressibility of the shallow stabilized ground and confining portion. h_1 is the thickness of shallow the stabilized ground. H_1 is the depth of the improved columns and $\Delta\overline{\sigma}$, the vertical load acting on the equivalent foundation. In the consolidation layer, the distributive load $\Delta\overline{\sigma}'$ is obtained from Eq. (9) under the assumption that vertical load $\Delta\bar{\sigma}$ is transferred from the equivalent foundation down to the bottom of consolidation layer.

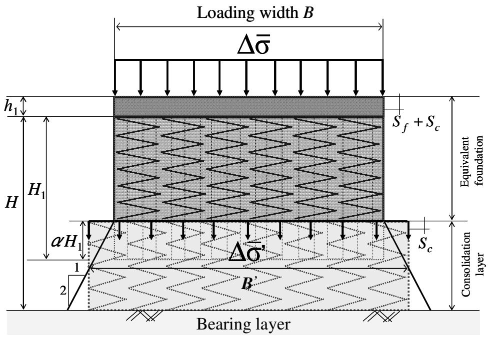

Figure 8. Concept for estimation of the total settlement.

Table 2. Parameters for calculating the settlement in detail.

Equivalent foundation		Case 1	Case 2
Coefficient of volume compressibility of shallow staibized ground	m_{vs} (m²/kN)	9.50E-06	9.50E-06
Thickness of shallow stabilized ground	h_1(m)	1	3
Coefficient of volume compressibility of confining portion	$\overline{m_{vf}}$ (m²/kN)	3.26E-05	7.03E-05
	$(1-\alpha)H_1$ (m)	4.4	2.7
Conversion load of embankment	$\Delta\bar{\sigma}$ (kPa)	101	109

Consolidation layer		Case 1	Case 2
Effective overburden pressure	p'(kPa)	53	76
Coefficient of volume compressibility of consolidation layer	m_v* (m²/kN)	8.80E-04	6.70E-04
Thickness of consolidation layer	$H-(1-\alpha)H_1$ (m)	3.6	4.1
Distributive conversion load of embankment	$\Delta\bar{\sigma}'$ (kPa)	93	100

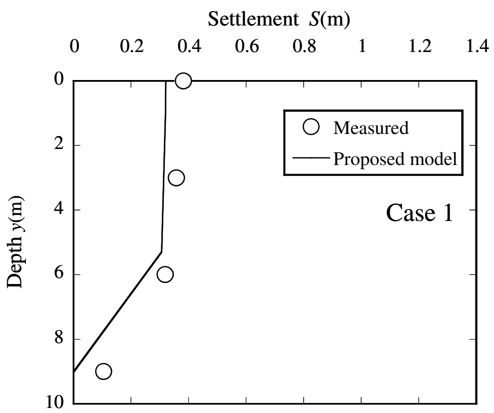

Figure 9. Comparison of calculated values with the measured ones .

$$\Delta\overline{\sigma'} = \Delta\bar{\sigma}\times\frac{B}{B'} = \frac{B}{B+\dfrac{H-(1-\alpha)H_1}{2}} \tag{9}$$

The settlement of the consolidation layer is obtained by Eq. (10).

$$S_c = m_v^*\{H-(1-\alpha)H_1\}\Delta\overline{\sigma'} \tag{10}$$

The total settlement of the improved ground is calculated by the summation of S_f and S_c as follows:

$$S = S_f + S_c \tag{11}$$

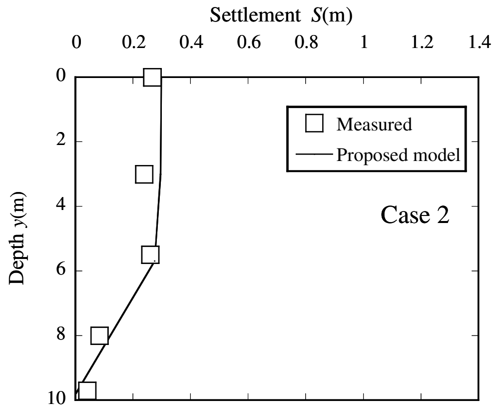

Figure 10. Comparison of calculated values with the measured ones.

4 COMPARISON WITH THE FIELD MEASUREMENTS

In this chapter, the field observation measurements in Chapter 2 are compared with the calculated values. The wet unit weight γ_t of embankment and soft soil were around 19.0kN/m³ in Chapter2. The void ratio e_0 and compression index C_c of the soft soil layer were about 1.80 and 0.60. On the basis of these parameters and Figures 6 and 7, the equivalent conversion ratio α can be obtained. The equivalent conversion ratios α in Cases 1 and 2 were around 0.33 and 0.51. Table 2 shows the parameters for calculating the settlement in detail.

The coefficient of volume compressibility of the consolidation layer m_v^* is obtained using the relationship between the initial void ratio e_0 and the overburden pressure p'.

The value of $\overline{m_{vf}}$ in the equivalent foundation is obtained by substituting the rigidity ratio $n_f = m_v^* / m_{vs}$ in Eq. (2).

The conversion load of embankment $\Delta\bar{\sigma}$ is obtained under the assumption that the load of the embankment acted uniformly on the improved area. Figures 9 and 10 show the comparison between the measured and values calculated in Cases1 and 2. The measured value implies the settlement just below the center of test embankment from the surface to the bottom.

In this proposed model, the improved ground was replaced with the layered ground that has an equivalent foundation and a consolidation layer. Therefore, the settlements of the improved ground change linearly in several layers. The measured values approximately correspond to the calculated values by this proposed model with a consideration for the skin friction applied around the surface of the floating-type column.

5 CONCLUSION

In order to estimate the settlement of in-situ improved ground using shallow stabilization and floating-type columns, a method for predicting the total settlement for this type of improved ground was proposed based on the homogenization method with a consideration for the stress distribution ratio. Its validity was confirmed from the field measurements. By this proposed model, it was clarified that the measured values of the settlement approximately correspond to the calculated values.

ACKNOWLEDGEMENT

The authors are grateful to Associate Professors Noriyuki Yasufuku, Kiyoshi Omine, Assistant Professor Taizo Kobayashi of Kyushu University, and Professor Hiroshi Matsuda of Yamaguchi University for their advice and encouragement.

REFERENCES

Ishikura, R., Ochiai, H., Omine, K., and Yasufuku, N. 2007. Estimation of the settlement of improved ground with a combined technology of shallow stabilization and floating-type cement treated columns, *J.Geotech. Engrg.*, JSCE , 63(4), pp.1101–1112 (in Japanese).

Miki, H. and Inoue, Y., and Okochi, Y. 2004. Comparison between observed data of full-scale test embankments on soft clay and 3D analysis, *4th seminar on soft ground improvement in high way construction*, pp.77–85.

Omine, K., and Ochiai, H. 1992. One-dimensional compression properties of sand-clay mixed soils based on soil structure, *JSCE*, No.457/III-21, pp.127–136 (in Japanese).

Ishikura, R., Ochiai, H., Yasufuku, N., Omine, K., and Kobayashi, T. 2006. Estimation of the settlement of improved ground with floating-type cement-treated columns, *Proc. of the Fourth International Conference on Soft Soil Engineering*, pp.628–635.