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Improvement in bearing capacity of shallow improvement ground by mixing short fibers

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ABSTRACT: Ground improvement technology such as a cement stabilization method has been applied to very soft ground in Japan. As for this method, cement-treated soil has relatively low tensile strength and shows very brittle behavior. It is therefore expected to use a fiber reinforcing material for improving mechanical property of the cement-treated soil. In this study, short fibers produced from waste paper were used as a reinforcing material in shallow improvement ground for increase of the tensile strength. Furthermore, model test of the improved ground was performed using loading device for applying uniform vertical stress corresponding embankment load. Improvement in bearing capacity of the shallow improvement ground with deep mixing columns was investigated under the different test conditions. The effectiveness of short fibers for improvements of deformation property and bearing capacity of the improved ground was confirmed from the test results.

1 INTRODUCTION

In the view point of geotechnical engineering, ground improvement technology such as a cement stabilization method has been applied to very soft ground in Japan. Cement-improved soil has some defects such as low tensile strength and brittle behavior, so that the defects may become a problem for application of shallow improvement method. It is also expected to use waste material as a fiber reinforcing material for improving mechanical property of cement-treated soil. Improvement in brittle behavior regarding deformation-strength property was discussed based on triaxial compression test of cement stabilized ground with various types of short fibers[1),2)].

In this paper, at first, in order to clarify improvement effect of reinforcing material with short fibers, simple bending test and tensile splitting test are performed.

Secondly, in order to evaluate bending stress of shallow stabilized ground with floating type deep mixing columns under uniform vertical stress conditions, bending stress model is proposed based on the idea of stress distribution ratio b.

Furthermore, model test of the improved ground is performed using loading device for applying uniform vertical stress corresponding embankment load. Short fibers produced from waste paper are used as a reinforcing material in shallow improvement ground. Improvement in bearing capacity of the shallow improvement ground with deep mixing columns is investigated under the different test conditions. The effectiveness of short fibers for improvements of tensile strength and bearing capacity of the improved ground and the validity of bending model are discussed based on the test results.

2 DEFORMATION-STRENGTH PROPERTY OF CEMENT-TREATED SOILS MIXED WITH SHORT FIBERS

2.1 *Soil sample and testing method*

First, short fibers were made by agitating waste paper with water in food processor and breaking into flocculate. Photo 1 shows the shapes of waste short fiber. Kaolin clay ($w_L = 50.6\%$, $I_p = 19.6$ and $\rho_s = 2.70\,g/cm^3$) is used as soil sample. After adding Portland cement to sample with water content of 100%, short fibers are mixed with it. The cement content C is 200 and 300 kg/m^3. After curing those specimens during 7 days in the thermostatic chamber of 20°C, each test is performed. Waste paper fiber content is 2.5 kg/m^3. Optimum fiber content changes in shape,

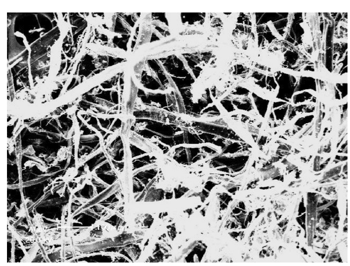

Photo 1. Shape of short fibers made from waste paper.

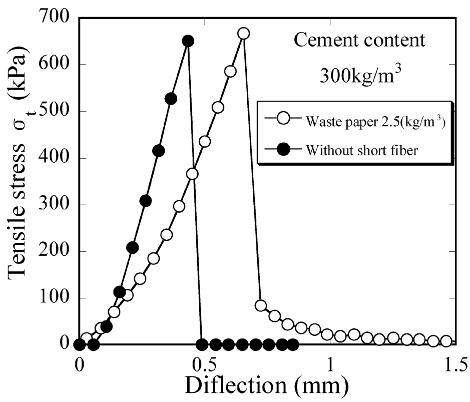

Figure 1. Relationship between tensile stress and deflection obtained from the bending test.

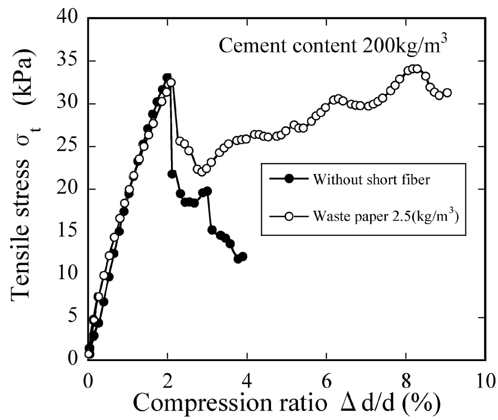

Figure 2. Relationship between tensile stress and compression ratio obtained from tensile splitting test.

length and kind of short fiber, and therefore the fiber content was decided in consideration of preliminary experiment. The specimen size of bending test is in the height of 40 mm and the width of 40 mm and the length of 160 mm. The specimen is supported by two fulcrums just below the specimen, and one is roller. Line load is applied on the center of upper surface by displacement control condition. The specimen size of the tensile splitting test is in the diameter of 150 mm and the height of 75 mm.

2.2 *Test result and discussions*

Figure 1 shows the relationship between tensile stress σ_t and deflection obtained from the bending test. Deflection is defined as the value of displacement center of specimen. As shown in this figure, tensile stress of the cement treated soil without waste paper becomes zero after reaching to the peak strength and shows a brittle failure. On the other hand, such brittle behavior is improved by mixing short fibers.

Figure 2 shows the relationship between tensile stress and compression ratio obtained from the tensile splitting test. Compression ratio is defined as the ratio between compressive displacement Δd and diameter of specimen d. As shown in this figure, the peak strengths of these two specimens are almost same. However, cement-treated soil without waste paper has a brittle failure after reaching to the peak strength. On the other hand, cement-treated soil with short fibers has a large residual strength after reaching to the peak strength.

In these tests, the effectiveness of short fibers for tensile strength of cement-treated soil was confirmed. In next chapter, in order to evaluate bending stress of shallow stabilized ground with floating type deep mixing columns under uniform vertical stress conditions, bending stress model is proposed.

3 ESTIMATION OF BENDING STRESS OF SHALLOW STABILIZED GROUND WITH FLOATING TYPE DEEP MIXING COLUMNS

In shallow stabilized ground with floating type deep mixing columns, vertical stress distribution has occurred between improved columns and soft clay just below the shallow stabilized ground. It is considered that larger bending stress of the shallow ground with the columns will occur than that of only shallow stabilized ground. So it is important to evaluate bending strength of shallow stabilized ground in these type improved conditions.

In this chapter, in order to evaluate tensile strength of shallow stabilized ground in uniform loading condition, an estimation method of bending stress of the shallow stabilized ground is proposed.

Figure 3 shows the concept of shallow stabilized ground with floating type deep mixing columns. As shown in this figure, bending stress of the shallow stabilized ground is discussed based on 1 unit of these type improved ground. Figure 4 shows the flow of estimation of bending stress σ_m of the shallow stabilized ground. In order to estimate bending stress of the shallow stabilized ground, it is important to determine stress distribution ratio b.

3.1 *Evaluation of stress distribution ratio with consideration of improved column rigidity and skin friction*

Figurer 5 shows the concept for the stress distribution ratio just below the shallow stabilized ground. The parameters of m_{vs} and m_v^* denote the coefficients of the volume compressibility of improved column and soft clay, respectively. When uniform vertical load p_1 is applied to the shallow stabilized ground, stress distribution just below the shallow stabilized

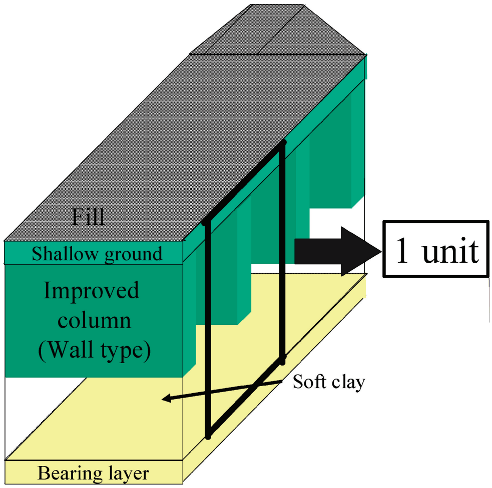

Figure 3. Concept of 1 unit of improved ground.

ground is represented using average stresses of soft clay and improved column, namely $\overline{p_2}$ and $\overline{p_3}$. This type improved ground remains soft clay just below the improved columns, so it is considered that skin friction around surface of the improved columns has occurred. The authors proposed stress distribution model with consideration of column rigidity and skin friction[3]. Stress distribution ratio b just below the shallow stabilized ground, which is defined by the ratio of $\overline{p_2}$ and $\overline{p_3}$, is expressed by Eq.(1).

$$b=\frac{\overline{p_3}}{\overline{p_2}}=\frac{2R(D+1)p_1+\left[\frac{(1-f_s)}{f_s}D+\frac{(f_sD+2)}{f_s(1-f_s)}R\right]\frac{\bar{\tau}A_s}{A_0}}{2(D+R)p_1-\left[D+\frac{(f_sD+2)}{f_s(1-f_s)}R\right]\frac{\bar{\tau}A_s}{A_0}} \quad (1)$$

where, R is the rigidity ratio ($=m_v^*/m_{vs}$), D is the depth ratio($=H_1/H_2$), A_0 is the area of improved ground, A_s is the sum of area around surface of improved column, f_s is ratio of the improved column in the improved ground, $\bar{\tau}$ is average skin friction around surface of improved column. In this paper, it is assumed that $\bar{\tau}$ is equal to the shear strength of soft clay c_u. The b value is calculated by the improved ground properties and improvement condition.

3.2 *Estimation of bending stress of shallow stabilized ground based on stress distribution ratio*

By the determination of stress distribution ratio b, bending stress σ_m is calculated as follows[4]. Figure 6 shows the concept of bending moment M of shallow stabilized ground. L_1 means distance between columns and L_2 means width of improved column. M is expressed in Eq.(2).

$$M = M_1 + M_2 \quad (2)$$

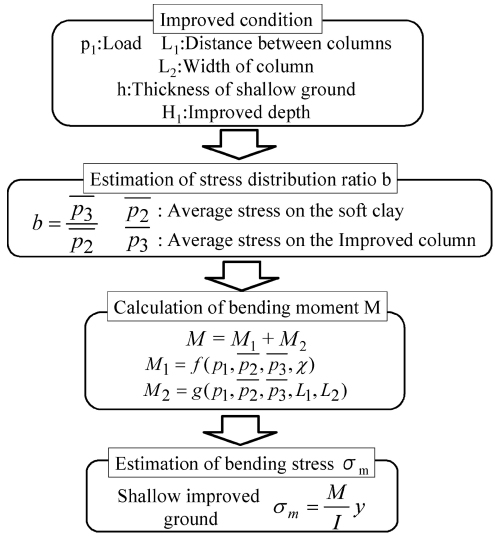

Figure 4. Flow of estimation of bending stress σ_m of shallow stabilized ground.

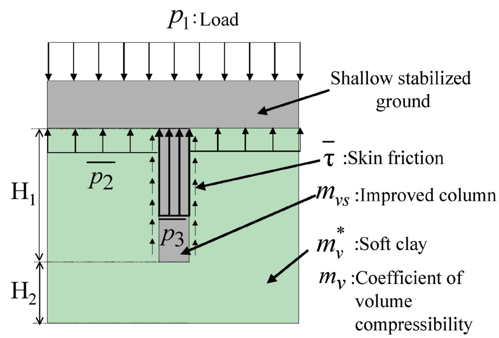

Figure 5. Concept of stress distribution ratio.

where, M_1 is obtained from the stress condition (p_1, p_2, p_3) and distance x from left edge of 1 unit, M_2 is defined as bending moment applied to the edges of shallow stabilized ground in 1 unit.

Secondly, deflection equation of shallow stabilized ground is expressed in Eq.(3).

$$\frac{d^2y}{dx^2}=-\frac{M}{EI} \quad (3)$$

where, E is deformation modulus of the cement-treated soil, I is geometrical moment of inertia of the shallow stabilized ground.

When deflection angle θ is equal to zero on the edges of the shallow stabilized ground in 1 unit, by substituting Eq.(2) to Eq.(3), M_2 is obtained as the function of p_1, $\overline{p_2}$, $\overline{p_3}$, L_1 and L_2, and consequently M value is obtained as the sum of M_1 and M_2.

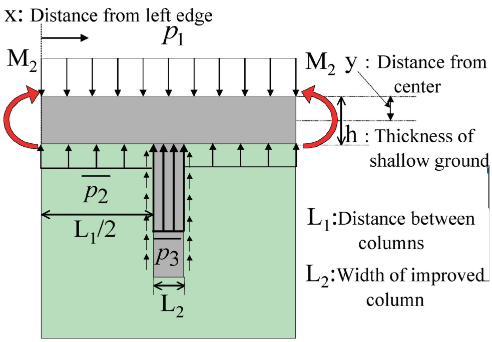

Figure 6. Concept of bending moment of shallow stabilized ground.

Finally bending stress of the shallow stabilized ground σ_m is obtained by the Eq.(4).

$$\sigma_m = \frac{M}{I} y \tag{4}$$

where, y is the distance from the center of thickness of shallow stabilized ground.

By substituting Eq.(2) to Eq.(4), bending stress σ_m of the shallow stabilized ground under uniform vertical stress condition is obtained. In next chapter, in order to confirm the validity of this model, loading model tests of the shallow stabilized ground with deep mixing columns under uniform vertical stress condition are conducted.

4 LOADING MODEL TEST OF THE SHALLOW STABILIZED GROUND WITH DEEP MIXING COLUMNS UNDER UNIFORM VERTICAL STRESS CONDITION

4.1 *Apparatus used in model test*

Figure 7 shows a schematic illustration of model test device. This device consists of a container box, loading device and 13 split loading plates. Displacements are measured on the loading plates of A and B in Figure 7. This loading model tests for the improved model ground were conducted under uniformed vertical stress-controlled condition using bellofram cylinders.

4.2 *Preparation of model ground and test procedure*

The model ground was prepared using soft clay and model columns. Kaolin clay was used as the soft clay. The Kaolin clay was mixed with a water content of about 80% and the slurry was poured into the container box up to a depth of approximately 260 mm. Soft clay was consolidated under pre-consolidation pressures of 10 and 20 kPa using a bellofram cylinder for around 2days. After pre-consolidation, a model ground with a height of 200 mm was obtained and the column was installed into the ground. A model column was used instead of the actual deep mixing columns in order to homogenize the rigidity of the columns. These columns are made from urethane and have a width of 20 mm and a height of 150 mm. By the unconfined compression test, the deformation modulus E of this column was approximately 50 MPa. Shallow stabilized ground was made by cement-treated soil for curing of 7 days.

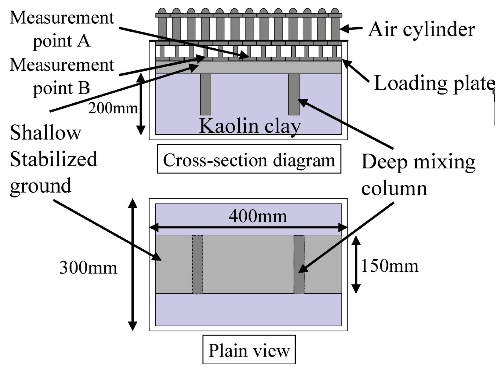

Figure 7. Schematic illustration of model test device.

Table 1. Test conditions of loading model test.

	Shallow ground thickness h (mm)	Depth deep mixing column H_1 (mm)	Cement content C kg/m^3	Waste paper content kg/m^3	Pre-consolidation stress p_0 kPa
Case-1	30	150	300	2.5	10
Case-2	30	150	200	2.5	10
Case-3	30	150	300	0	10
Case-4	30	150	300	0	20

4.3 *Test conditions*

After completing model ground, the loading model tests were carried out under an undrained condition.

Loading stress is applied at a whole area of shallow stabilized ground using 13 split loading plate of 30 mm width. In order to apply the load uniformly, model ground is covered with sand of approximately 20 mm height. Displacements are measured in two points , namely (A) center between model columns and (B) upper side of the model column. Table 1 shows test conditions of loading model test. Improvement ratio f_s is 10% in each case. Shallow stabilized ground thickness is 30 mm and depth of deep mixing column is 150 mm in all test conditions. In order to confirm the effectiveness of short fiber for improvement

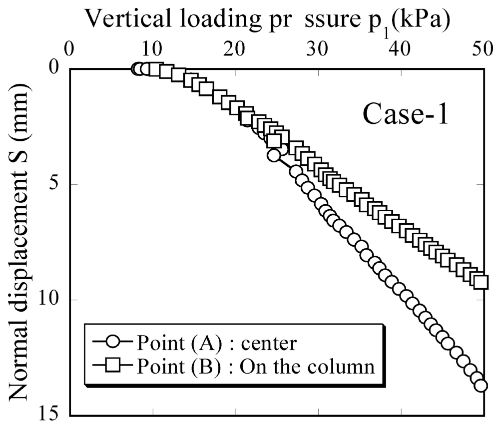

Figure 8. Relationship between vertical loading pressure p_1 and normal displacement S (Case-1).

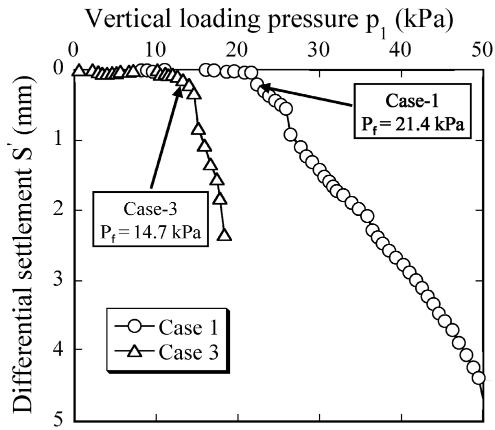

Figure 9. Relationship between vertical loading pressure p_1 and differential settlement S'.

of tensile strength, cement-stabilized ground in Case-1 and 2 contains waste paper. For making clear the influence of soil property, test condition of different pre-consolidation pressure p_0 was used in Case-3 and 4 of non-mixture.

4.4 *Test result and discussions*

Figure 8 shows the relationship between vertical loading pressure p_1 and normal settlement S of measurement point (A) and measurement point (B) in Case-1. As shown in this figure, the improved ground does not show clear peak strength and brittle failure such as observed in the bending tests. So it is difficult to recognize tension failure of the shallow stabilized ground under uniform vertical loading condition. On the other hand, difference of settlement between measurement points (A) and (B) becomes large with an increase in the vertical loading pressure p_1.

Figure 9 shows the relationship between differential settlement S' and vertical loading pressure p_1 in Case-1 and 3. Differential settlement S' means difference of settlements between measurement points (A) and (B). Each differential settlement S' is very small in low vertical loading pressure level. However, differential settlement S' increases with increase in the vertical loading pressure p_1 in all test cases. In this model test, yielding pressure p_f of the shallow stabilized ground is defined as vertical loading pressure at the rapid increase of differential settlement in each case. As shown in this figure, yielding pressure p_f of shallow stabilized ground in Case-1 is larger than that of Case-3, that is to say, the effectiveness of short fibers for tensile strength of cement treated soil was confirmed under the uniform vertical stress condition.

Improvement in bearing capacity of the shallow improvement ground by mixing short fibers is also confirmed by vertical loading pressure-differential displacement curve in comparison with Case-1 with short fiber and Case-3 without short fiber.

Table 2. The parameter used in the estimation of bending stress σ_m of shallow stabilized ground.

	Case-1	Case-2	Case-3	Case-4
Tensil strength σ_t (kPa)	618	294	296	541
Calculated value of stress distribution ratio b	5.01	7.37	7.71	8.34
Soft clay of coefficient of volume compressibility m_v^* (m^2/MN)		6.007		1.628
Improved column of coefficient of volume compressibility m_{vs}(m^2/MN)		0.02		

4.5 *Comparison between experimental and calculated values*

In this section, in order to confirm the validity of bending stress model based on stress distribution ratio in chapter 3, experimental values of vertical loading pressure p_f are compared with calculated values in occurring tension failure of the shallow stabilized ground.

Table 2 shows the parameters used in the estimation of bending stress σ_m of shallow stabilized ground. Tensile strength σ_t means the average value for 3 specimens of bending test in each case. In order to evaluate tensile strength of shallow stabilized ground using in the model test size, it is considered that scale effect on strength of cement-treated soils is one of influence factors. Omine et al. suggested an estimation method for predicting the scale effect[5)]. Tensile strength of shallow stabilized ground for the model test size can be

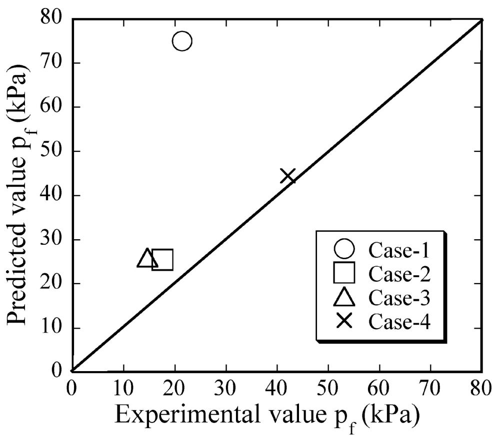

Figure 10. Comparison between calculated and experimental value p_f of uniform vertical stress.

estimated from that of standard size specimen by this model. Tensile strength of shallow stabilized ground for the model test size σ_s is expressed by tensile strength reduction coefficient α and σ_t. α is obtained from average tensile strength value and standard deviation of bending test in each case. Relationship between σ_s and σ_t is $\sigma_s = \alpha\sigma_t$. In calculating this model test, the value of α value becomes 0.66.

Stress distribution ratio b just below the shallow stabilized ground is estimated by Eq. (1). Parameters within Eq. (1) are determined by the initial ground and boundary conditions and vertical loading pressure p_1, that is to say, b value is depended on vertical loading pressure p_1. Bending moment M of shallow stabilized ground is determined by $\overline{p_2}$ and $\overline{p_3}$ obtained from relationship between b and p_1. By substituting bending moment M into Eq.(4), bending stress σ_m is obtained. Namely, when p_1 value is determined, bending stress σ_m is also obtained.

Calculated value p_f at tension failure of shallow stabilized ground is defined as the value obtained from relationship between p_1 and σ_m when σ_m is equal to σ_s of tensile strength of shallow stabilized ground with consideration of scale effect.

Table 2 also shows the calculated value of stress distribution ratio b when σ_m is equal to σ_s.

Experimental value p_f is defined as the p_1 value at the rapid increase of differential settlement shown in Figure 9.

Figure 10 shows the comparison between the calculated and experimental value p_f. As shown in this figure, calculated values in Case-2 and 3 approximately correspond with the experimental results. Calculated value in Case-1 is larger than that of experimental. It is considered that tensile strength σ_t in this Case become larger than that of other cases in spite of the same curing day and cement content. In order to investigate the influence of soil property, pre-consolidation pressure p_0 in Case-4 is different from other cases. As shown Table 2, b value in this Case becomes larger than other cases. It is considered that the undrained shear strength of soft clay c_u increases with the increase in pre-consolidation pressure p_0. Calculated value in Case-4 also approximately corresponds with the experimental result in different condition of soil property.

5 CONCLUSIONS

The main conclusions obtained from this study are as follows;

1) Brittle behavior of cement-treated soil in bending test and tensile splitting test are improved by mixing short fibers.
2) Yielding pressure of shallow stabilized ground mixed with short fibers is increased under the condition of uniform vertical pressure and bearing capacity characteristic is also improved.
3) Bending stress of shallow stabilized ground with deep mixing columns under the condition of uniform vertical pressure can be estimated by the bending stress model based on stress distribution ratio.

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