Prediction of strength of cement-treated soil column based on size effect

Prédiction basée sur l'effet de grandeur de la résistance de colonnes ballastées traitées au ciment

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ABSTRACT: The strength of the cement-treated soils is influenced by the specimen size. It is therefore important to predict the in-situ strength of the cement-treated soils from that of a small size specimen in a laboratory. A new probabilistic failure model has been proposed in this study. This model is applied to unconfined compressive strength, tensile strength and bending strength of cement-treated soils. The validity of this method is confirmed by the results of laboratory tests and loading test on the improved ground with cement-treated soil columns.

RÉSUMÉ: La force des sols ciment-traités est influencée par la taille de spécimen. Il est donc important de prévoir la force in-situ des sols ciment-traités de cela d'un petit spécimen de taille dans un laboratoire. On a proposé un nouveau modèle probabiliste de panne dans cette étude. Ce modèle est appliqué à unconfined la résistance à la pression, la résistance à la traction et la résistance de la flexion des sols ciment-traités. La validité de cette méthode est confirmée par les résultats des essais en laboratoire et de l'essai de chargement sur la terre améliorée avec les colonnes ciment-traitées de sol.

1 INTRODUCTION

Size effect on the strength of brittle materials like rocks or concretes has been investigated and some statistical theories, for example, a weakest link model or a bundle model, have been applied. On the other hand, cement-treated soil made by Deep Mixing Method or surface soil stabilization is a material between rocks and soils in a viewpoint of the strength. The strength of the cement-treated soils is also influenced by specimen size, so that prediction of strength on the cement-treated soils is one of the important problems in geotechnical engineering.

In order to confirm the validity of the proposed model, unconfined compression, splitting tensile and bending tests were performed. The result calculated from this model is compared with the laboratory test results and the previous experimental results of the in-situ cement-treated soils. This method is also applied to improved ground with cement-treated soil columns.

2 EVALUATION OF SIZE EFFECT BY STATISTICAL METHOD

There are some probabilistic failure models for evaluating the size effect on the strength. The concepts of the failure models are shown in Figure 1. An average model is applied to ductile materials like clays. On the other hand, a weakest link model is often applied to brittle materials. It is explained that the size effect on the strength is caused by the existence of flaws or potential cracks distributed in the specimen. In the weakest link model, the strength of the specimen is decided by the weakest crack and then it will represent a lower bound of the strength. A bundle model has been proposed by Daniel (1948) and Hasofer (1968). The strength of the bundles of threads is obtained by the consideration of the maximum load that the bundle can support. Honjo (1982) applied this model to cement-treated soils using the computational method.

It may be said that the weakest link model and the bundle model express size effects for the length and width of the specimen, respectively. In this study, a new failure model is proposed by combining the weakest link model and the bundle model. A fundamental concept for evaluating the size effect in the combined model is shown in Figure 2. It is assumed that a number, n_0, of the cracks is distributed in a standard size specimen in the diameter of d_0 and the height of h_0. The weakest link model is applied to a piece of stick with the diameter, d_0, and the height, h. The number, n, of the cracks in the stick is in proportional to the volume of the specimen. The strength of the stick is decided by the weakest one among n cracks.

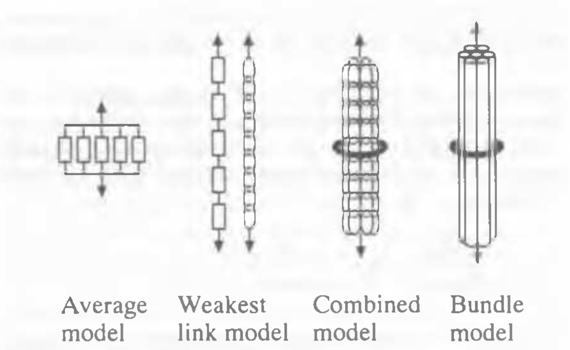

Figure 1. The concepts of the probabilistic failure models.

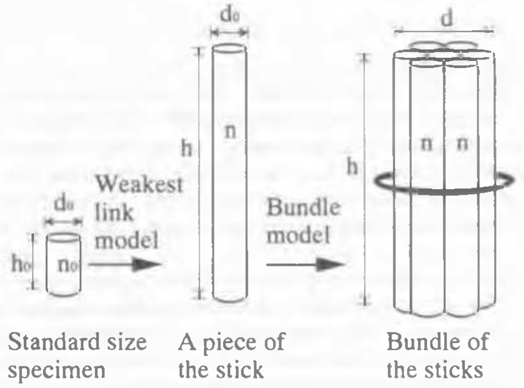

Figure 2. Fundamental concept of the combined model.

This problem is to obtain a probability of the weakest value when sampling n cracks from a population. Next, the strength for a bundle of the sticks is evaluated based on the idea of the bundle model. It is assumed that all constituent sticks have the same elastic modulus and the residual strength is zero. Namely, the broken sticks beyond failure stress do not support the stress and the survival sticks sustain the uniform stress. It is considered that the strength in the combined model is between the weakest link model and the bundle model. By assuming similar function of the weakest link model, the compressive strength, s_c, in the combined model is derived as follows (Omine et al., 1998),

$$\dot{s}_c = \left\{ (1 - \sqrt{a}) \left(\frac{d}{d_0} \right)^{-1/\beta} + \sqrt{a} \right\}^2 \left(\frac{h}{h_0} \right)^{-1/\beta} \dot{s}_{c0} \tag{1}$$

where

$$a = (\beta - 1)^{-1/\beta} \exp\left(-\frac{1}{\beta} \right) \tag{1-1}$$

$$\omega = \frac{\sqrt{\Gamma(1 + 2/\beta) - \Gamma^2(1 + 1/\beta)}}{\Gamma(1 + 1/\beta)} \tag{1-2}$$

and subscript '0' means a standard size specimen, ω is coefficient of variance for the strength, Γ is Gamma function, a and β are constants which are obtained by ω.

In a similar manner, a formula of size effect on the splitting tensile strength is derived by combining these models. The splitting tensile strength, s_t, is therefore represented as follows,

$$\dot{s}_t = \left\{ (1 - a) \left(\frac{h}{h_0} \right)^{-1/\beta} + a \right\} \left(\frac{d}{d_0} \right)^{-2/\beta} \dot{s}_{t0} \tag{2}$$

where a and β are the same as Eqs.(1-1) and (1-2). However, it should be noted that the coefficient of variance, ω, in the splitting tensile test is different from that in the unconfined compression test.

Furthermore, the combined model is also applied to the specimen in bending test in a similar way that the weakest link model has been applied for evaluating the bending strength. Consequently, the bending strength, s_b, obtained from this model is represented as

$$\dot{s}_b = \left\{ (1 - a) \left(\frac{W}{W_0} \right)^{-1/\beta} + a \right\} \left(\frac{HL}{H_0 L_0} \right)^{-1/\beta} \dot{s}_{b0} \tag{3}$$

where H, L and W are height, length and width of the rectangular specimen, respectively.

3 VERIFICATION OF THE PROPOSED MODEL

3.1 *Comparison between calculation and test results*

In order to confirm the validity of the proposed model, unconfined compression, splitting tensile and bending tests were performed. Kaolin clay (w_L=50.6%, I_P=19.6, ρ_s=2.70g/cm^3) was used as original soil. Cement-treated soil samples were made by mixing portland cement in a ratio of water and cement, w/c=1.0, into a slurry clay with water content of 100%. The specimen size for the unconfined compression tests is a diameter, d=20, 40, 83 and 150mm, and a height of h=2d. The cement content is 300kg/m^3. The specimen size in the splitting tensile tests is d=20, 40, 83, 150 and 300mm and h=d/2. The cement contents are of 150 and 300kg/m^3. The specimen size in the bending tests is H=20, 40, 100 and 150mm and H=W=L/4. The cement content is 300kg/m^3. These specimens were cured for 7days.

The specimen with a diameter d=40mm is used as a standard size here. Figure 3 shows the probability density for the unconfined compressive strengths of the cement-treated soils. As shown in this figure, the probability density of the strength is expressed approximately by Weibull's distribution.

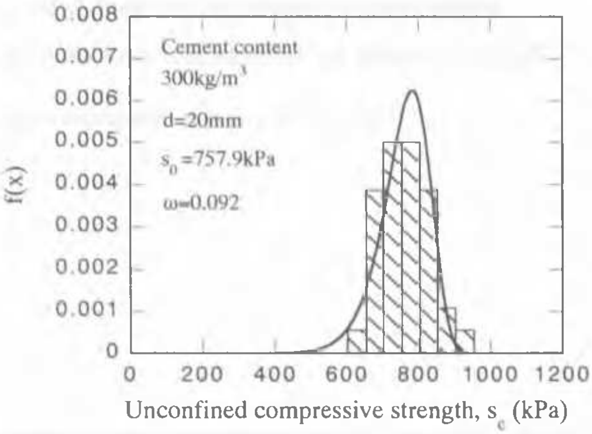

Figure 3. Probability density for unconfined compression test of the cement-treated soils.

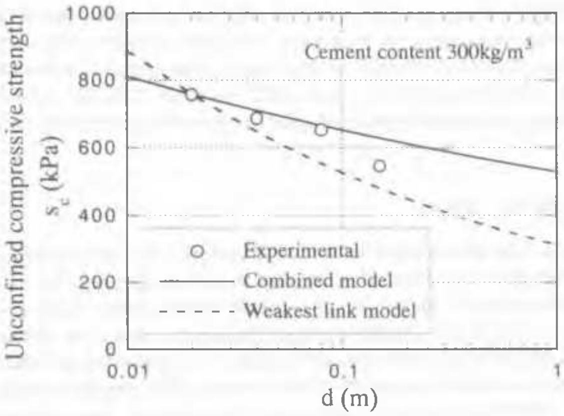

Figure 4. Comparison between the experimental and calculated results for the unconfined compressive strength of the cement-treated soils.

The comparison between the experimental and calculated results for the unconfined compressive strength of the cement-treated soils is shown in Figure 4. Both calculated curves in the combined model and the weakest link model are also shown. The strength in the combined model is calculated by Eq.(1). The parameters, s_c and ω, were obtained from standard size specimen.

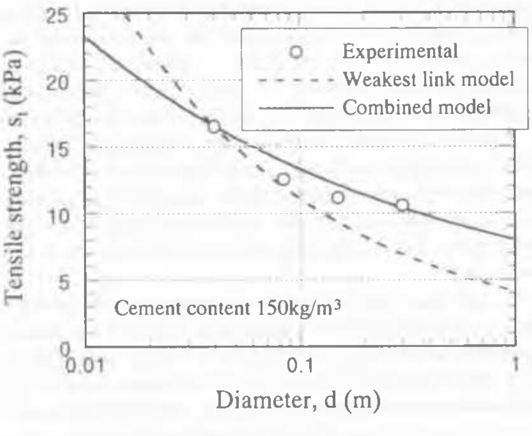

Figure 5. Comparison between the experimental and calculated results for the tensile strength of the cement-treated soils.

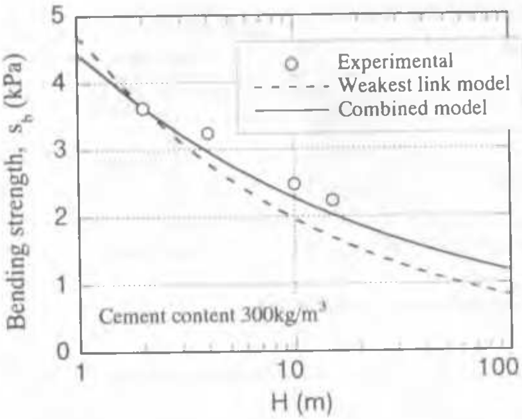

Figure 6. Comparison between the experimental and calculated results for the bending strength of the cement-treated soils.

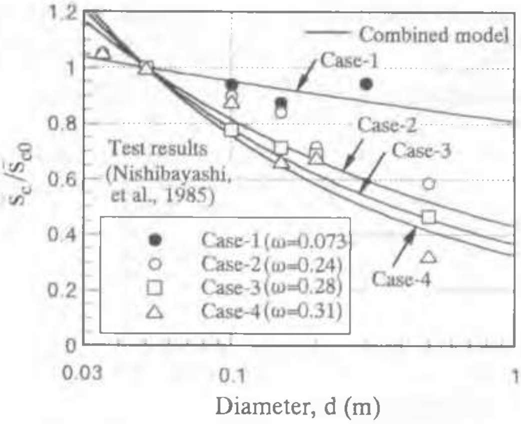

Figure 7. Comparison between the results of model mixing test and the calculated results by the proposed model.

When a=0 in Eq.(1), this equation becomes the same as the weakest link model. As shown in the figure, it is obviously that the size effect exists on the unconfined compressive strength. Comparing with the weakest link model, the combined model expresses the test results well. The comparison between the experimental and calculated results in the tensile strength of the cement-treated soils is shown in Figure 5. The tensile strength decreases remarkably with the increase of the specimen size. Although the weakest link model underestimates the strength of the large size specimen, the calculated result obtained from the combined model gives a good agreement with the test results. Furthermore, the size effect on the bending strength is shown in Figure 6. The bending strength of the cement-treated soils decreases with the same trend as the tensile strength. Thus, the proposed model can estimate the strength of the cement-treated soils from that of the small size specimen.

3.2 *Comparison with the previous experimental results*

The size effects on the strength of the cement-treated soils have been studied by some researchers. In this section, the proposed model is compared with the previous experimental results.

Nishibayashi et al. (1985) performed the model mixing tests for clarifying the influence of the uniformities of the cement-treated soils and the differences in sample diameter. Kawasaki marine clay was used and cement-treated soils with the different mixing level were prepared. The comparison between the test results of the unconfined compression tests and the calculated results by the proposed model are shown in Figure 7. The mixing level for the specimens of Case-1 is very high because of being made by a large soil mixer. Hence, the coefficient of variance, ω, in this case is very small. The specimens of Case-2~4 were made in the difference mixing level using the model mixing apparatus and the difference size specimens were sampled from the treated soil columns in d=500mm being in a real size. As shown in this figure, the strength of the cement-treated soils normalized by that of the standard size specimen in d=50mm decreases with the increase of the specimen size and the large size effect appears. The degree of the size effects depends on the coefficient of variance. The test results support the concept of the statistical model considering a distribution of the strength. The combined model can evaluate the strength of the cement-treated soils with the different uniformity and the different specimen size.

3.3 *Comparison with in-situ strength of cement-treated soil*

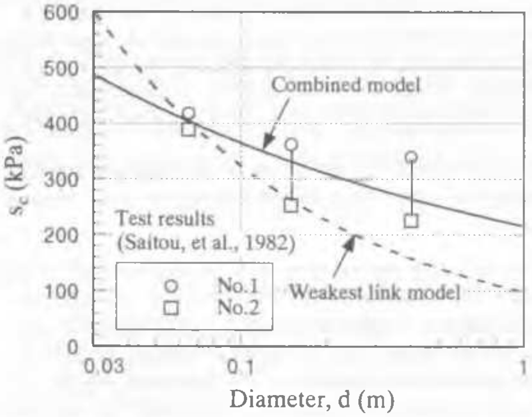

Figure 8. Comparison between the test and calculated results for unconfined compressive strength of in-situ cement-treated soils.

Test results on the size effect for the in-situ cement-treated soils made by Deep Mixing Method has been reported (Saitou et al., 1982). Specimens of different size were sampled from the columns for unconfined compression tests. The comparisons between the test and calculated results for the in-situ treated soils are shown in Figure 8. The calculated curves in the combined model and the weakest link model are also shown together with the test results. It is generally reported that the coefficient of variance for the strength of the small size specimens is in a range of 0.2~0.3. The value of ω=0.2 is used in the calculation of the models. Although the weakest link model underestimates the strength of the in-situ treated soils, the combined model gives a good agreement with the test results. It is therefore confirmed that the combined model is available for evaluating the size effect on the strength of the cement-treated soils.

Thus, the proposed model can predict the strength of the cement-treated soils in a large size from the strength properties of a small size specimen.

4 PREDICTION OF THE STRENGTH OF THE CEMENT-TREATED SOIL COLUMNS

4.1 *Prediction of strength of the cement-treated soil column*

It is difficult to measure directly the strength of the in-situ treated soil column in large size. The combined model evaluates the scale effect on the strength of the specimens of different diameter and height. In this section, the strength of the cement-treated soil column estimated by the combined model is discussed.

The relationship between the unconfined compressive strength of the cement-treated soil column and the coefficient of variance is shown in Figure 9. The unconfined compressive strength of the cement-treated soil columns of d=1m is calculated from Eq.(1) using average strength of the standard size specimen of d_0=0.05 and h_0=0.1m. The strength of the cement-

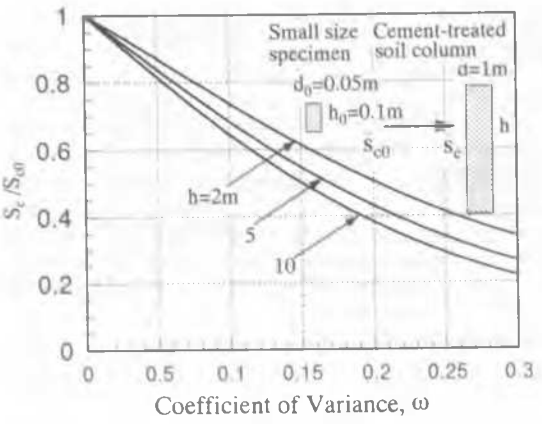

Figure 9. Prediction of unconfined compressive strength of the cement-treated soil columns.

treated soil column decreases remarkably as the coefficient of variance increases. In-situ condition, a confining pressure is applied to the cement-treated soil columns, so that the scale effect may be somewhat small as compared with this results. However it is important to predict the strength of the cement-treated soil column from the strength of the small size specimen in a laboratory.

Thus, the combined model is one of the effective methods for evaluating the size effect on the strength of the cement-treated soils.

4.2 *Bearing capacity of improved ground*

In order to confirm the validity of the proposed model for improved ground by Deep Mixing Method, loading model tests with different size were performed. The schematic diagram of the model test is shown in figure 10. The model ground was made by inserting the cement-treated soil columns made with mold in advance into Kaolin clay with water content of 80%. The bearing capacity of improved ground was calculated from both strengths of the cement-treated column and the original soil as a composite material. However, the original soil is very soft, so that the bearing capacity is almost decided with the strength of the cement-treated column in the condition of this experiment. The results of loading model tests and the prediction curve of the combined model are shown in Figure 11. The parameters in the calculation were obtained from the average strength and the coefficient of variance of the cement-treated soil in a diameter of 40mm and the strength of the cement-treated column for each size was calculated by Eq.(1). As shown in the figure, it is found that the size effect exists on the bearing capacity of improved ground. The prediction curve based on the proposed model can express well the experimental results.

5 CONCLUSIONS

The main conclusions obtained from this study are as follows;

1) A new probabilistic failure model was proposed by combining the weakest link model and the bundle model.
2) The validity of the combined model was confirmed by comparing with the unconfined compression, splitting tensile and bending test results of the cement-treated soils.
3) The combined model gives a good agreement with the previous experimental results of sampling specimen from the in-situ cement-treated soil columns and the loading model test results on the improved ground.
4) The strength of in-situ cement-treated soil columns is predicted by the combined model. It is shown that the strength of cement-treated soil column decreases remarkably with increasing in the coefficient of variance.

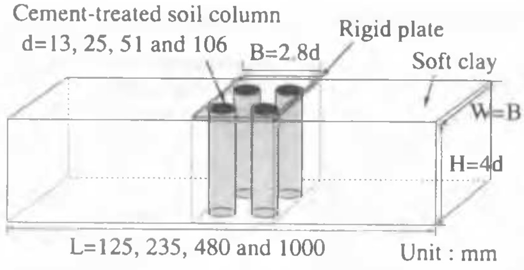

Figure 10. A general view of the model test.

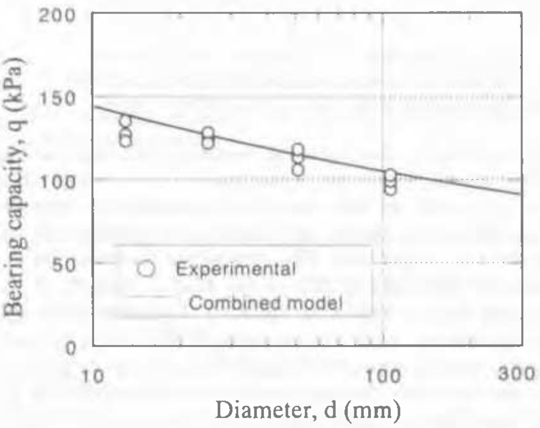

Figure 11. Comparison between calculation and test results for the bearing capacity of improved ground.

5) This method is available for predicting the strength of in-situ cement-treated soil column from that of small size specimen.

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