Study on failure mechanisms of the deep mixing columns reinforced by a shallow mixing layer

Etude sur les mécanismes d'échec des colonnes de mélange profond renforcées par une couche de mélange peu profound

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ABSTRACT: Centrifuge model tests were carried out to investigate the failure pattern of the deep mixing columns beneath an embankment slope. The columns in this study were fixed and reinforced by a cement stabilized shallow layer in order to increase the horizontal resistance of the group of columns. This study focused on both the external and internal failure mechanisms of the deep mixing columns. For the external stability, acrylic piles and acrylic plate were used to simulate the improved area in order to avoid any internal failure taking place inside the columns. The fixed type and floating type columns were also used to investigate the effect of bottom strength beneath improved area on the failure of columns. In another hand, the soil cement mixing was used to make low strength columns and a shallow layer which were used to study the internal failure mechanism of the combined structure. In addition, simple calculation, based on equilibrium method, was also conducted to evaluate the failure patterns obtained from centrifuge model tests. The effect of a shallow layer on changing the failure pattern of columns was also discussed in this study.

RÉSUMÉ : Des tests sur un modèle centrifuge ont été réalisés pour étudier le motif d'échec des colonnes de mélange profond sous un talus. Les colonnes dans cette étude ont été fixées et renforcées par une couche superficielle stabilisée par du ciment pour augmenter la résistance horizontale du groupe de colonnes. Cette étude a porté sur les deux mécanismes de défaillance externes et internes des colonnes de mélange profond. Pour la stabilité externe, des piles acryliques et une plaque en acrylique ont été utilisés pour simuler la zone améliorée afin d'éviter toute défaillance interne qui se déroule à l'intérieur des colonnes. Les colonnes de type fixe et les colonnes de type flottant ont également été utilisées pour étudier l'effet de la force de fond sous une zone ameliorée sur l'échec des colonnes. D'autre part, le mélange du ciment du sol a été utilisé pour diminuer la force des colonnes et une couche superficielle qui ont été utilisées pour étudier le mécanisme de défaillance interne de la structure combinée. En outre, un simple calcul, basé sur la méthode d'équilibre, a également été réalisé pour évaluer les motifs d'échec obtenus à partir des essais sur un modèle centrifuge. L'effet d'une couche superficielle sur le changement du motif d'échec des colonnes a également été abordé dans cette étude.

KEYWORDS: deep mixing, shallow mixing, failure pattern, centrifuge model test, embankment

1 INTRODUCTION

The Deep Mixing Method (DMM), a deep in-situ soil stabilization technique using cement and/or lime as a binder, has been often applied to improve soft soils. Group column type improvement has been extensively applied to foundations of an embankment or lightweight structures. The design procedure for the group column type DM ground has been established for the application of embankment, in which two failure patterns are assumed: sliding failure in the external stability and rupture breaking failure in the internal stability. It is well known that the deep mixing columns tend to fail either external failure or internal failure depending on the ground condition such as the column strength (Kitazume & Maruyama, 2006, 2007).

Due to the low horizontal resistance of the isolated columns, a cement stabilized shallow layer was proposed to fix and reinforce the isolated columns in order to increase the resistance. The application of this combined structure was reported by several researchers (Chai *et al.*, 2010; Ishikura *et al.*, 2009; Kitazume, 2011). However, the failure pattern of the combined improved ground with the shallow layer and the deep mixing columns has not well studied yet. In this study, eight centrifuge model tests were conducted to investigate the failure mechanism of the improved ground and the effect of the shallow layer. In the external stability, the fixed type and floating type columns were also investigated the failure mechanism. According to the centrifuge model tests, the effect of the improvement width on the failure patterns was discussed together with a simple calculation based on load equilibrium method. A good agreement between the centrifuge model tests and the calculation confirmed the observed failure mechanism of the isolated columns as well as the columns with shallow layer reinforcement.

2 CENTRIFUGE MODEL TESTS

2 .1 *Model ground*

The model ground was prepared in a stiff container whose inside dimensions are 150 mm x 500 mm with 362 mm in height. The front window of the container was made by transparent acrylic for visual observation during centrifuge flight. Figure 1 shows an example of the model ground, in which the soft ground layer of 200 mm in thickness deposits on the stiff layer at the bottom with 30 mm in thickness. In the preparation, Silica No. 3 sand was poured into the container to make a drainage and stiff layer at the bottom. The Kaolin clay slurry, with the water content of 100 %, was then poured on the Silica layer and one-dimensionally consolidated under the pressure of 200 kPa. After the consolidation, the undrained shear strength of Kaolin clay was measured at about 30 kPa (water content of 60 %). Then, the front window of the container was disassembled for attaching the optical marker, 10 mm long nails, as can be seen in the figure. The noodles were also placed to observe possible failure lines in the model ground. After re-assemble of the window, model columns and a shallow layer were installed in the ground. In the improved area, 12 columns of 20 mm in diameter were arranged in a square pattern with the center-to-center spacing of 37.5 mm. For the model ground with the shallow layer, a 40 mm thick shallow layer was constructed to fix and reinforce the group of 12 isolated columns. In this study, eight centrifuge model tests were conducted to study the failure pattern of the deep mixing columns as shown in Table 1. For investigating the external failure mechanism of the improved area, the acrylic material was used instead of cement stabilized soil for the deep mixing columns and the shallow layer in order to avoid their failure (Case 1, 2, 3 and 4). The deep mixing columns and the shallow layer were tightly connected by screws, with an assumption of a rigid connection. For the case of the internal failure (Case 5, 6, 7 and 8), the cement stabilized soil was used for the columns and the shallow layer. As shown in Table 1, two sets of columns' strength were targeted to study its effect on the failure pattern. Although the shallow layer was made with the same mixing condition, its strength was found smaller than that of columns probably due to shorter curing time, when the shallow layer was made and cured inside the container for 14 days.

2 .2 *Preparation and procedure*

As assuming the bisymmetric condition, a half-side embankment was modeled. For constructing the embankment, an in-flight sand hopper was used based on the sand rainfall technique. Zircon sand was used as an embankment material, as its large specific gravity of 4.66 for achieving the model ground failure at 50 g centrifugal acceleration. Two earth pressure gauges were placed under the embankment center to measure the embankment pressure during constructing.

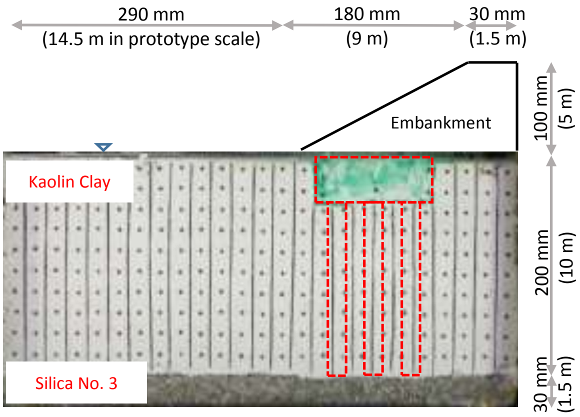


Figure 1. Model ground of centrifuge model tests

Table 1. Test cases

Test cases	Test condition	Columns & SL materials	Columns' q_u (kPa)	SL's q_u (kPa)
Case 1	Fixed type columns - without shallow layer	Acrylic		
Case 2	Fixed type columns - with shallow layer	Acrylic		
Case 3	Floating type columns - without shallow layer	Acrylic		
Case 4	Floating type columns - with shallow layer	Acrylic		
Case 5	Fixed type columns - without shallow layer	Soil-cement	533.1	-
Case 6	Fixed type columns - with shallow layer	Soil-cement	533.1	269.7
Case 7	Fixed type columns - without shallow layer	Soil-cement	258.3	-
Case 8	Fixed type columns - with shallow layer	Soil-cement	258.3	164.1

* q_u: Unconfined compressive strength; SL: shallow layer

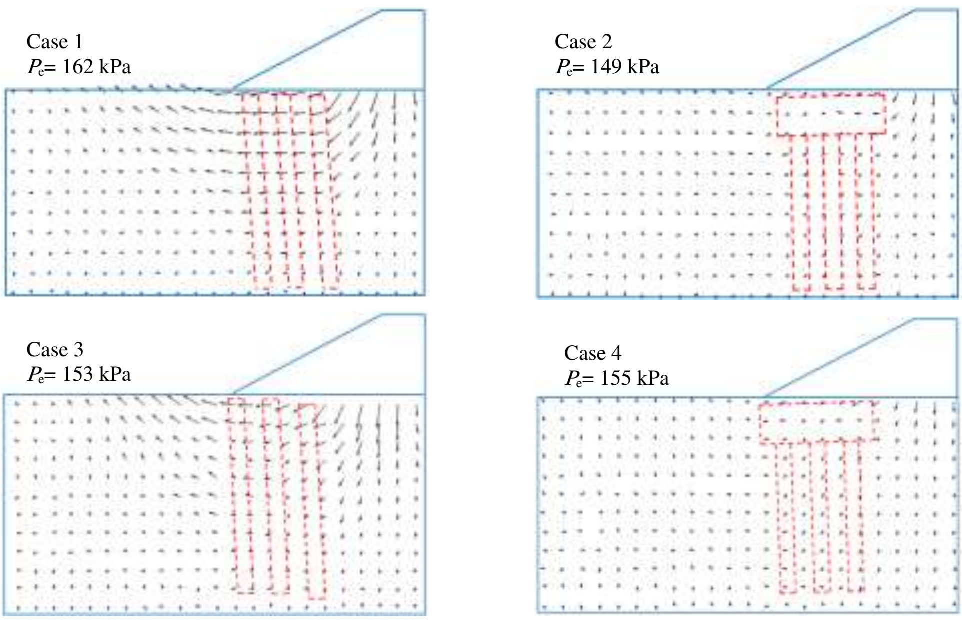


Figure 2. Displacement of model ground in Cases 1, 2, 3 and 4

3 RESULTS AND DISCUSSIONS

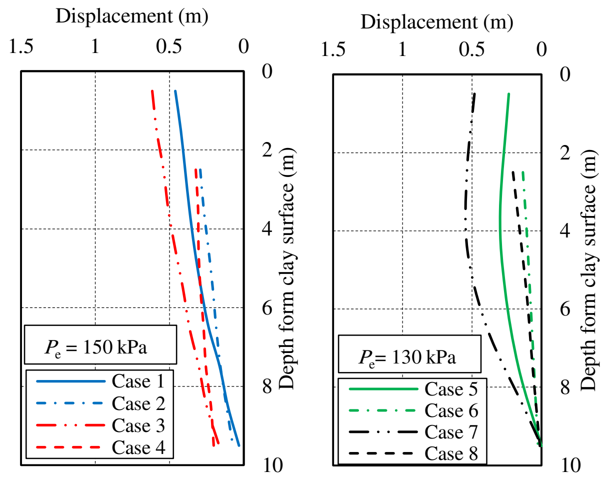
3 .1 *External failure*

Prototype scale is used for presenting the results as well as for discussion from this section. The final deformations of the model ground are shown in Figure 2 for Cases 1, 2, 3 and 4, together with the final position of improved area. An obvious failure of the isolated columns with a large displacement of model ground can be observed in Cases 1 and 3. However, clear ground failure was not observed in the case of the shallow layer reinforcement (Cases 2 and 4). For detail discussion, Figure 3(a) shows the horizontal displacement of the middle column at the embankment pressure, P_e of 150 kPa. From the figure, the large tilting displacement was found in Cases 1 and 3 irrespective of the fixed type or floating type columns, where the DM columns were not reinforced by the shallow layers. Similar displacement phenomenon was also observed in the previous study (Kitazume & Maruyama, 2006). In the case of reinforced by the shallow layer (Cases 2 and 4), on the other hand, the tilting displacement of the columns was quite small by the effect of the reinforcement irrespective of the fixed type or floating type columns. It is found from the model tests that the shallow layer has the large effect on the column displacement; the tilting displacement of columns is dominant in the case of no reinforcement by the shallow layer (Cases 1 and 3), the overturning displacement of whole improved area in the case of the fix type ground with the reinforcement (Case 2) and the sliding failure in the case of the floating type ground with the reinforcement (Case 4).

3 .2 *Internal failure*

For the internal failure, the final deformations of model ground in Cases 5, 6, 7 and 8 were presented in Figure 4 together with the final position of improved area. In these tests, the embankment loading was terminated when several cracks were expected to take place in the columns, for ease of observation of the column failures after the test. As can be seen in the figure, clockwise bending deformation of the columns was clearly observed in Cases 5 and 7 irrespective of column strength. Together with the bending deformation, tensile cracks were also found at the middle depth of the columns. Due to the failure of the columns, the model ground experienced large deformation. The effect of column strength on reducing the deformation of model ground was also confirmed from the figure. In particular, although the test in Case 7 was stopped at lower embankment pressures comparing to that in Case 5, the model ground displacement was greater in Case 7 with lower strength columns.

For the model ground with the shallow layer in Cases 6 and 8, on the other hand, the failure pattern of the improved area



(a) External stability. (b) Internal stability.
Figure 3. Columns deformation (middle columns)

was different from that without the shallow layer; no failure took place along the columns but the tensile cracks took place at the connection between the shallow layer and columns in Case 8. In Case 6, the embankment loading was terminated at low embankment pressure to investigate the minor failure of the columns. As shown in Figure 4, small cracks were found in all three columns while the failure state of model ground did not reach.

To compare the columns' deformation amongst four internal stability tests, the deformation of middle columns in Cases 5, 6, 7 and 8 at the same embankment pressure of 130 kPa were plotted together in. In the case of no reinforcement (Cases 5 and 7), it is found that large horizontal displacement of the column was found together with the bending deformation. The larger horizontal displacement took place in the smaller column strength (Case 7). In the case of the reinforcement (Cases 6 and 8), quite small horizontal displacement took place. The test results reveal that the large effect of the shallow layer and the column strength on reducing columns displacement and deformation. Similar phenomenon on the effect of column strength as well as bending failure mechanism were reported by previous studies (Kitazume & Maruyama, 2007; Kitazume, 2011; Tatarniuk & Bowman, 2012; Zheng *et al.*, 2013).

3 .3 *Evaluation of failure patterns*

For discussion on the failure pattern, a simple calculation was conducted based on the load equilibrium method by the previous research (Kitazume & Maruyama, 2006, 2007) and Rankin's earth pressure theory. Three failure patterns were considered in the external stability; the tilting failure of individual columns, the sliding failure and the overturning failure of improved area. In the internal stability, the shearing bending failure in the column and the shear failure in the shallow layer were considered. Figure 5 shows the relationship between the embankment height at each failure pattern and the improvement width, which are calculated for the centrifuge model test conditions with two column strengths.

For the calculations with q_u = 100 kPa (Figure 5(a)), the overturning failure shows large embankment height at failure, H_e among the external stability (sliding and tilting failures). In the case of the fix type improvement, the sliding failure shows large H_e that is almost same as the overturning failure, but quite small H_e value in the floating type. The tilting failure shows a slightly greater H_e value than that in the sliding of the floating type. For the external failure, the tilting failure can take place in the fix type improvement, but the sliding or the titling failure can take place in the floating type. In the internal stability, three failure patterns, shearing and bending in the column and the shearing in the shallow layer show almost the same H_e value, while the shearing in the column is the lowest. This indicates that the stabilized soil fails in the column or in the shallow layer with various failure patterns at an almost same time. By comparing the external and internal failures, it can be said that the titling failure or the shearing failure takes place in the fixed type, while the sliding or shearing failure takes place in the floating type.

For the calculations with q_u = 500 kPa (Figure 5(b)), the same relationships as the low strength case can be found in the external stability. In the internal stability, three failure patterns, shearing and bending in the column and the shearing in the shallow layer show larger H_e value as the strengths of the column and shallow layer increase. Among the three failure patterns, the shear failure in the shallow layer shows the largest H_e value while the bending in the column shows the lowest. It can be estimated that the titling failure in the external stability or the bending failure in the internal stability will take place in the fix type improvement, while the sliding or tilting failure in the external stability will take place in the floating type improvement.

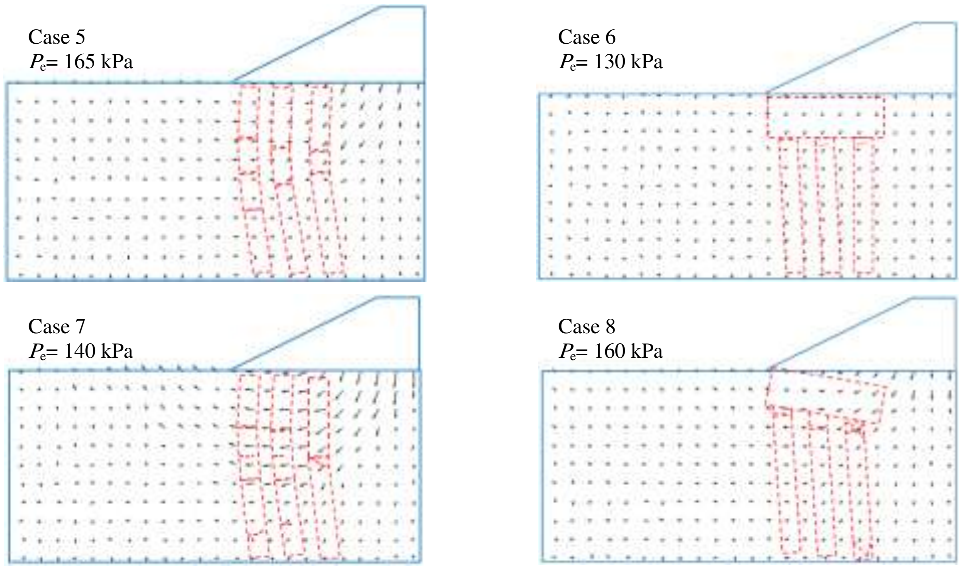
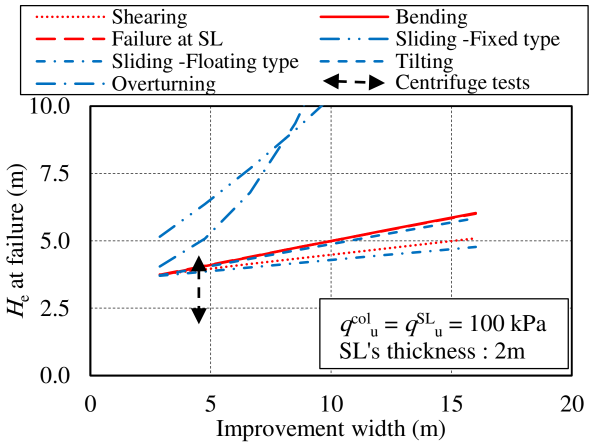
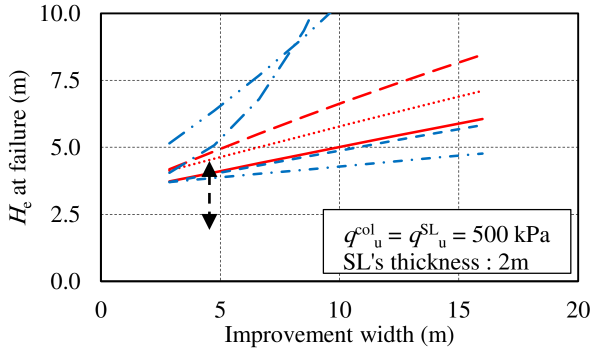


Figure 4. Displacement of model ground in Cases 5, 6, 7 and 8



(a) For $q^{col}_u = q^{SL}_u = 100$ kPa.



(b) For $q^{col}_u = q^{SL}_u = 500$ kPa.

Figure 5. Embankment height at failure (H_c)

In Figure 5, the centrifuge model test results are also plotted together. As the series of the model test was carried out on the ground with the improvement width of 4.75 m only, the effect of the improvement width on the failure pattern could not be observed, unfortunately. The model ground failed with various combinations of the external and internal failure patterns in the centrifuge test, it is quite difficult to identify which failure pattern took place first and how the failure patterns extended with the embankment loading. However, it can be said that the tilting failure can be one of the dominant failure patterns in the external stability, and the shearing and bending failure in the column can be one of the dominant patterns in the internal one, which corresponds the simple calculations shown in Figure 5.

4 CONCLUSIONS

A series of centrifuge model tests was carried out changing the column strength and shallow layer reinforcement to investigate their effects on the failure pattern and embankment height at failure. A simple calculation was also conducted to investigate the effect of improvement width. According to the centrifuge model tests and the simple calculations, based on equilibrium method, the failure pattern is influenced by the ground conditions, especially by the shallow layer reinforcement. As far as the test conditions, the tilting failure can be one of the dominant failure patterns in the external stability, and the shearing and bending failure in the column can be one of the dominant patterns in the internal one.

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