Internal stability of group column type deep mixing improved ground on inclined foundation layer

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ABSTRACT

A group column type deep mixing (DM) improved ground has frequently been applied to increase stability of embankment on a soft ground. The design standard for the DM improved ground has been established in Japan, in which the two failure patterns are assumed: external and internal stabilities. The stability design of the improved ground on an inclined foundation is also evaluated based on the design standard, though the standard assumes that the improved ground is placed on a horizontal foundation. The authors conducted a research project on the failure mechanism and stability of group column type DM improved ground on an inclined foundation. In this study, the internal stability of DM columns on an inclined foundation layer was investigated by a series of centrifuge model tests and FEM analyses. The study reveals that the external and internal stabilities of the improved ground are decreased almost linearly with the inclination of foundation irrespective of the strength of stabilized columns.

Key words: deep mixing method, soft ground, internal stability, centrifuge model test, FEM analysis

1 INTRODUCTION

Soft soil deposits are often encountered in many construction projects, where large ground settlement and ground failure are anticipated. The Deep Mixing Method (DMM), a deep in-situ soil stabilization technique using cement, has often been applied to improve soft soils (CDIT, 2002; Kitazume and Terashi, 2013). Group column type improvement, where many DM columns are constructed in rows with the rectangular or triangular arrangement, has been extensively applied to foundation of embankment or lightweight structure. A design procedure for the group column type DM improved ground has been established in Japan (PWRC, 2004). The two failure patterns are assumed in the design: external and internal stabilities. The external stability examines the possibility of sliding and overturning failures of the improved ground, while rupture breaking failure is evaluated in the internal stability.

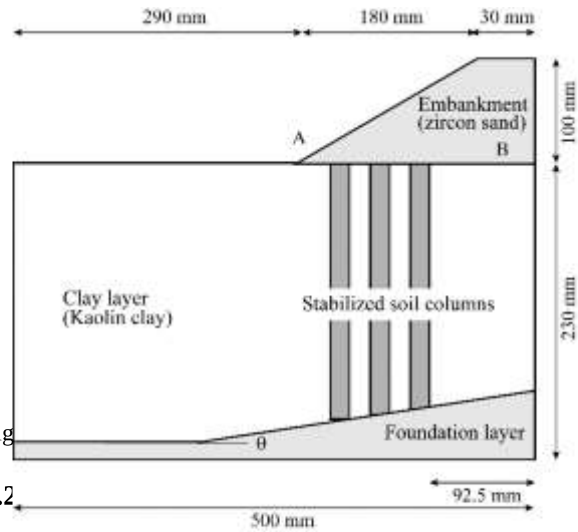
The ground behavior of the group column type improved ground under embankment has been investigated by many model tests (e.g. Akamoto and Miyake, 1989; Kitazume and Maruyama, 2006, 2007; Nguyen *et al*., 2017a, 2017b), the numerical analyses (e.g. Han *et al*., 2005; Filz and Navin, 2006; Adams *et al*., 2009; Nguyen *et al*., 2015) and the design calculation (Kitazume, 2008). However almost all researches focused on the DM columns sitting on a horizontal foundation, and little research focused on the DM columns sitting on an inclined foundation. Though the behavior and failure pattern of DM columns on an inclined foundation may be different from those on a horizontal foundation, the current design based on the horizontal foundation has been simply applied to the inclined foundation in some case histories.

The authors conducted a research project on the failure mechanism and stability of group column type DM improved ground sitting on an inclined foundation. Its external stability was investigated by the centrifuge model tests and FEM analyses (Toshinari *et al*., 2017). In this manuscript, the effect of the foundation inclination on the internal stability of DM columns was investigated by the centrifuge model tests and FEM analyses.

2 CENTRIFUGE MODE TEST

2.1 Model ground preparation

A series of model tests was carried out in the TIT Mark III Centrifuge in order to simulate the prototype stress condition (Takemura *et al*., 1999). A rectangular model container was used, the inside dimensions of which are 150 mm in width, 500 mm in length and 362 mm in depth, respectively. One of the model grounds is exemplified in Fig. 1, which consists of Kaolin clay layer, model DM columns, inclined foundation and embankment. The Kaolin clay was consolidated with 200 kPa pressure to obtain an over-consolidated ground with the uniform shear strength of 30 kPa in a laboratory. Cement stabilized soil columns were produced by mixing Kaolin clay of 160 % in the initial water content and ordinal Portland cement of cement content of 10 % for the target unconfined compressive strength of 500 kPa. The model improved ground was constructed by installing the model columns with 3 rows and 4 lines into the Kaolin clay ground. The ground was subjected to an embankment loading at the 50 *G* acceleration field to cause the ground failure. The detail of the model ground preparation can be referred to the manuscript (Toshinari *et al.*, 2017). Three model tests were carried out changing the inclination of foundation layer: a horizontal foundation (Case I.S-1) and two inclined foundations with θ = 10 and 30 deg. for Cases I.S-2 and I.S-3 (Fig. 1).



Fig

2.2

the model ground at the 50 *G* to simulate the undrained loading condition. Figure 2 shows the relationship between the horizontal displacement at embankment toe (point A in Fig. 1) and embankment pressure. In Case I.S-1, the horizontal foundation, the horizontal displacement was increased almost linearly with the embankment pressure but rapidly when the pressure exceeded about 130 kPa. Similar phenomenon can be seen in Cases I.S-2 and I.S-3, an inclined foundations, in which the horizontal displacement was increased rapidly at about 130 kPa for Case I.S-2 and about 90 kPa for Case I.S-3.

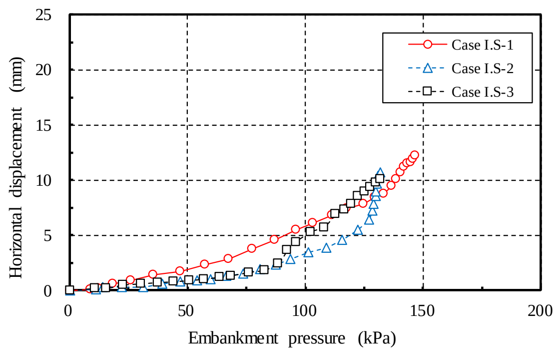
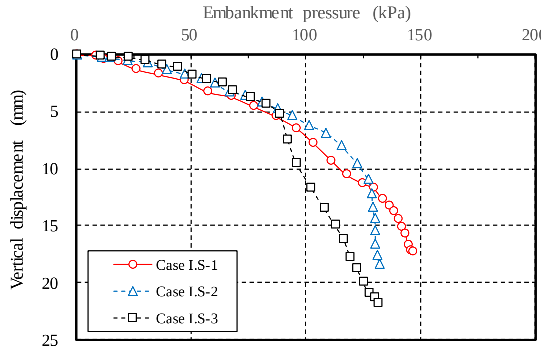


Fig. 2. Horizontal displacement and embankment pressure.

The relationship between the vertical displacement at the ground surface (point B in Fig. 1) and embankment pressure is shown in Fig. 3. In Case I.S-1, the vertical displacement was increased gradually with the embankment pressure and then rapidly when the embankment pressure exceeded about 130 kPa. This phenomenon is consistent with that in the horizontal displacement as shown in Fig. 2. In Cases I.S-2 and I.S-3, the vertical displacement was increased gradually at beginning but increased rapidly when the embankment pressure exceeded about of about 90 kPa for Case I.S-2 and about 130 kPa for Case I.S-3, which are consistent with those in the horizontal displacement (Fig. 2).



Fig

2.3 Failure pressure and inclination of foundation

The ground failure is defined when the vertical and horizontal displacements were increased rapidly with the embankment pressure. The embankment pressure at failure thus obtained is shown in Fig. 4 along the inclination of foundation. It can be seen that the embankment pressure at failure decreases almost linearly with the inclination. The failure pressure at the inclination of 30 deg. is about 70% of that of the horizontal foundation case. In the figure, the relationship for the external stability is plotted together (Toshinari *et al.*, 2017). The embankment pressure at failure for the external stability is decreased slightly with inclination of foundation. By comparing them, the embankment pressure at failure for the internal stability shows larger decrease with the inclination than those for the external stability.

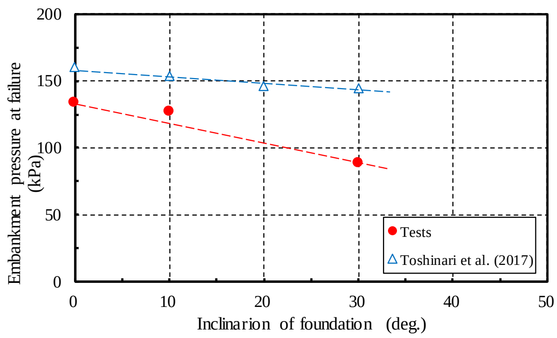


Fig. 4. Embankment pressure at failure and foundation inclination.

2.4 Horizontal displacement distribution

The horizontal displacement distribution along the depth at embankment toe was measured by the PIV and shown in Fig. 5 at the various embankment pressures. In Case I.S-1, horizontal foundation, Fig. 5(a), a small linear horizontal displacement was observed at the embankment pressure of 60 kPa. The horizontal displacement was increased rapidly with the embankment pressure, particularly at the shallow to middle depth, while the displacement at the bottom of column was negligible. When the embankment pressure was increased to 147 kPa, quite large horizontal displacement of about 180 mm can be seen at the middle depth. In Case I.S-2, an inclined foundation of 10 deg., Fig. 5(b), small displacement can be seen at the embankment pressure of 60 kPa, which is similar to the horizontal foundation case, Case I.S-1. With the increase of embankment pressure, the horizontal displacement was increased rapidly along the depth, particularly at the shallow to middle depth. The maximum displacement was found at the depth of about 145 mm at the embankment pressure of 132 kPa, which was little shallower than that in Case I.S-2. In Case I.S-3, inclination of foundation of 30 deg., Fig. 5(c), similar phenomenon can be seen, where the horizontal displacement was increased with the increase of embankment pressure. The maximum displacement was found at the depth of about 70 mm at the embankment pressure of 131 kPa.

After the embankment loading test, the clay ground was excavated to observe the DM columns' failure in detail. The deformation and bending failure points of the most front DM column of the second row from the box window are ilustrated together in Fig. 5. It is found that the bending failures took place at various depths in all three columns irrespective of the inclination of foundation and the deformation of DM column was almost coincided with the horizontal displacement profile at the embankment toe.

3 FEM ANALYSES

3.1 Conditions

In order to confirm the centrifuge model test results and investigate the effect of the stabilized soil column strength on the ground failure, a series of FEM analyses was carried out. In the analyses, PLAXIS 2D was used for the two dimensional condition, where the cylindrical shape model stabilized soil columns were simulated as a rectangular shape wall according to Ariyarathne *et al*. (2012). All the model ground materials were modeled as the Mohr-Coulomb elast-plastic material whose soil parameters are tabulated in Table 1.

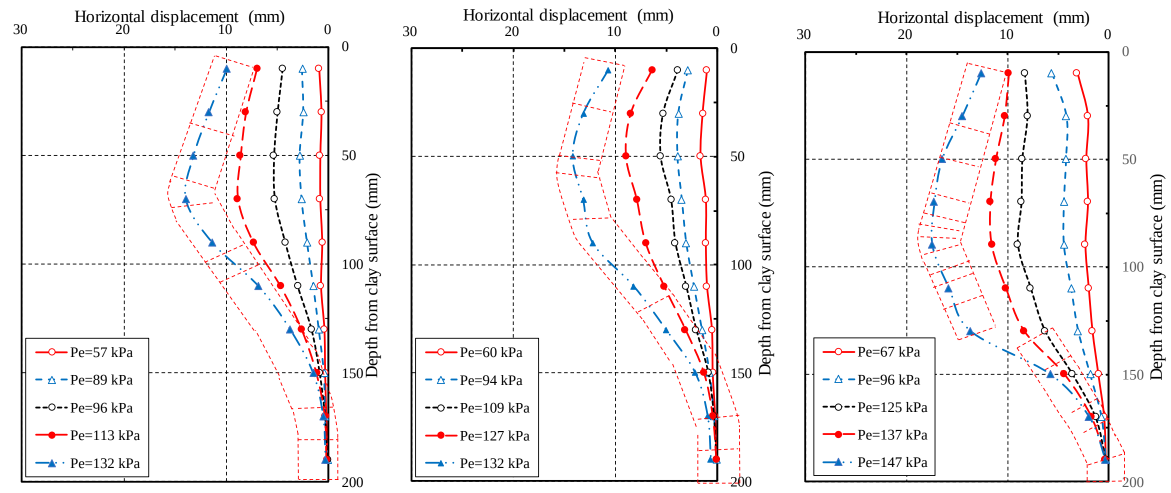
Table 1. Soil parameters in the analyses.

	γ_t, kN/m^3	c', kN/m^2	ϕ', deg.	E', MN/m^2	K_0
clay	16.6	30	0	0.7	0.5
foundation	14.5	1	30	100	0.5
column	16.6	250	0	140	0.5
embankment	33.3	2	30	10	0.5

3.2 Calculation results and discussion

The embankment pressure was increased to investigate the ground behavior, where the stabilized soil columns were deformed and tilted. In the case of the large column strength, the titing displacement was dominant with negligible bending deformation. The overturning failure, one of the external failure, of the improved ground was defined when the horizontal displacement at the embankment toe was increased rapidly with the increase of embankment pressure. The embankment pressure at the overturning failure is plotted along the inclination of foundation by the blue and solid lines in Fig. 6. The figure shows the embankment pressure at failure is almost linearly decreased with the increase of inclination, while it is increased with the increase of column strength.

In the case where the column strength was relatively small, on the other hand, the column was titled with large bending deformation. The bending failure of the column,



(a) Case I.S-1. (b) Case I.S-2. (c) Case I.S-3.

Fig. 5. Horizontal displacement distribution along depth.

one of the internal failure, was defined when the induced bending stresses in the columns exceeded the column strength and the bending deformation of the columns was increased significantly. The embankment pressure at the bending failure of the column is plotted by the red and broken line together in Fig. 6. The figure shows the embankment pressure at failure was also decreased with the increase of inclination of foundation, while its magnitude was also influenced by the column strength.

The DM improved ground can be assumed to fail by one of the failure modes, which gives the minimum failure pressure in the given ground condition. Figure 6 shows that the improved ground fails by either the overturning failure or the bending failure depend on the column strength, where the bending failure takes place in the case where the column strength is relatively small and the overturning failure takes place when the column strength is relatively large. The figure clearly shows that the embankment pressure at failure is decreased almost linearly with the increase of inclination of foundation irrespective of the failure mode, which indicates the c ... ty of i

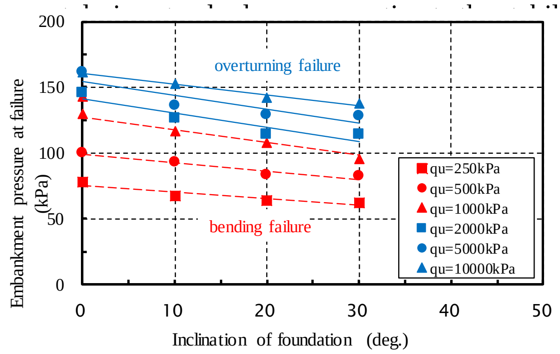


Fig. 6. Embankment pressure at failure and foundation inclination.

4 CONCLUSIONS

In this study, a series of centrifuge model tests and FEM analyses were carried out to investigate the effect of inclination of foundation on the deformation and internal stability of the column type DM improved ground subjected to the embankment loading. The study revealed that the improved ground fails by either the overturning failure mode or the bending failure mode depend on the column strength and the embankment pressure at failure is decreased almost linearly with the increase of inclination of foundation ground irrespective of the failure mode. The current design standard may overestimate the stability of improved ground on an inclined foundation.

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