Numerical analyses on the failure of deep mixing columns reinforced by a shallow mixing layer

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ABSTRACT

Soil cement mixing by deep mixing technique is used as a soft soil improvement method. Deep mixing columns are widely used to support embankment constructed on a soft ground area. In order to applying this improvement method, the failure pattern of group column type improvement should be analyzed. Researches on the failure pattern of columns are done by some authors when the columns individually fail. Due to individual failure of columns under loading, a layer of shallow mixing layer is proposed to reinforce individual columns working as a group in order to increase the stability as well as loading capacity of columned improved area. This research focuses on the failure pattern of group of columns which are fixed by the shallow mixing layer under embankment. By comparing to failure mechanism of individual columns, the effect of shallow mixing layer on failure pattern of deep mixing columns is also discussed. Finite element method is used for this analysis with Plaxis code under plain strain condition. The effect of thickness of shallow mixing layer on reducing horizontal displacement of embankment is various with different values of strength and stiffness of cement mixing area which is discussed in this research.

Keywords: deep mixing, shallow mixing, failure pattern, numerical analysis, embankment

1 INTRODUCTION

Cement or lime and soil mixing technique was firstly used in Japan and Nordic countries since 1960s. The technique is used to improve soft soil by increasing its mechanical properties including strength and consolidation characteristics (Kitazume & Terashi, 2013). A lot researches were done to investigate the characteristics of mixing material due to many factors including types of binder, condition of soil, mixing condition and curing condition (Terashi, 1997). On the other hand, many studies have focused on the application of in-situ mixing technique such as supporting embankment and underground structure as well as working as the foundation of building and factory (Kitazume & Terashi, 2013). In term of embankment supporting, column-type improvement is taken into account for a huge application. Due to loading from embankment, the deep mixing columns tend to fail either externally (Kitazume & Maruyama, 2006) or internally (Kitazume & Maruyama, 2007). However, the deep mixing columns do not fail simultaneously but instead one by one at different time (Kitazume & Maruyama, 2007). By using a shallow mixing layer to fix the top of deep mixing columns, individual columns may work simultaneously. A combination of shallow and deep mixing was also proposed to reduce settlement of a high embankment on soft ground (Ishikura et al., 2009). However, the failure pattern of shallow and deep mixing combined structure has not well studied yet. This research focuses on the failure mechanism of the combined structure by using numerical method. The effect of shallow mixing layer on the failure of deep mixing columns is investigated with various strength and stiffness of columns and shallow layer. The effect of thickness of shallow mixing layer on embankment’s displacement and the embankment pressure at yield of the improved ground is also discussed in this study.

2 SOIL CONDITION AND SOIL PROPERTIES

2.1 Soil condition

In this analysis, an embankment is assumed to be built on a ground with two layers which is typical in real cases of embankment construction on soft soil condition. The detailed soil condition used in this study is showed in Fig. 1.

In the improvement area, five columns with 1.0 m in diameter are arranged from the toe to the center of the embankment. With a 2.0 m spacing between columns, the improvement width is taken to 13.0 m. It is noted that the improvement area ratio in this case is 33.3 %, a popular ratio for deep mixing column improvement applications.

The thickness of shallow mixing layer is changed

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during the calculation in order to study its effect on the deep mixing column failure pattern. The width of shallow mixing layer is within the 5-column area which is equal to 13.0 m.

![Diagram of Soil Condition](image)

**Fig. 1. Soil condition**

The embankment is constructed on the clay layer improved by the deep and shallow mixing layer which is divided into layers for constructing. Each layer with 0.25 m thickness is built step by step in the analysis until column's failure happens. Research by Take & Valsangkar (2001) pointed out that a narrow backfill behind a retaining wall may cause smaller horizontal stress distribution on the wall. In order to avoid the effect of this problem, a large distance from embankment center to improved area is preferred in this study.

### 2.2 Soil properties

Based on the research done by former authors, soil properties are proposed as Table 1. $K_0$ values are assumed for each material to stimulate relationship between horizontal and vertical stresses at rest state. The shallow mixing layer material is taken the same material as the deep mixing column. However, the strength as well as stiffness of the mixing material will be changed in the calculation to study its effect on the failure of columns. The unconfined compression strength ($q_u$) of mixing materials is assumed from 250 kPa to 5000 kPa in order to investigate both internal failure and external failure patterns of columns. From $q_u$ value, shear strength and Young modulus are estimated as Eq. 1 (Kitazume & Terashi, 2013).

$$c_u = \frac{q_u}{2}, \quad E = 200q_u$$

| SOIL         | $\gamma_{sat}$ | $\gamma_{unsat}$ | $c_u$ | $\varphi'$ | $E$ | $\nu$ |
|--------------|-----------------|-------------------|-------|------------|-----|-------|
| Embankment   | 16              | 18                | 1.0   | 30         | 20,000 | 0.3   |
| Clay layer   | 14              | 16                | 25    | 0          | 2,500  | 0.45  |
| Sand layer   | 16              | 18                | 0     | 35         | 20,000  | 0.3   |
| Deep mixing  | 14              | 16                | Changed | 0      | Changed | 0.45  |

**Table 1. Soil properties**

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### 3 NUMERICAL METHOD

The embankment construction process is modelled by finite element method (FEM) with Plaxis 2011 Code in plain strain condition. In order to simulate the improvement area in plain strain condition (2D simulation) from the 3D natural condition of deep mixing columns, the column-type improvement will be simulated as wall-type improvement by keeping the same improvement ratio of 33.3% in this analyses. As a result, the wall thickness will be thinner the real diameter of the deep mixed column in the simulation.

The vertical boundaries are horizontal fixities while the bottom boundary is full fixities. To be more detailed, at the vertical boundary, soil element as well as water are not allowed to move horizontally but vertically. Similarly, at the lowest geometry line (or bottom boundary) the full fixities are mean that it is not allowed soil element as well as water at this boundaries to move in both vertical and horizontal directions.

The embankment and sand layer are considered as drained behavior materials while the clay layer behaves in undrained condition during the loading process. All these materials are modelled by Mohr-Coulomb model with elasto-perfectly plastic behavior. Mixing materials including the deep mixing columns and shallow mixing layer are both modelled in undrained condition.

### 4 RESULT AND DISCUSSION

#### 4.1 Failure pattern without shallow mixing layer

The horizontal displacement at the toe of embankment increases with loading steps as shown in Fig. 2 with different values of $q_u$. The failure of embankment can be observed with a large horizontal displacement which is shown in the vertical axis in the figure at 170 kPa embankment pressure.

![Graph of Embankment Pressure and Horizontal Displacement](image)

**Fig. 2. Embankment pressure and horizontal displacement curves**

Details of embankment pressure at yield can be detected by a clear bending point so-called yield point from the loading and displacement curve. The detecting
yield points are presented in Fig. 3 in relationship with the unconfined compressive strength of deep mixing columns \((q_u)\). From the figure, the embankment pressure at yield increases with \(q_u\) value.

Fig. 3. Embankment pressure at yield and \(q_u\) value

The deformations of columns were observed by the displacement at center of columns. Figure 4 shows the deformation of deep mixing column in case of without shallow mixing layer for four different \(q_u\) values of columns. Columns with \(q_u = 5,000\) kPa experience a tilting deformation under 170 kPa of embankment pressure while others are clearly bent at 160 kPa of embankment pressure with low strength columns, especially with \(q_u = 250\) kPa.

Fig. 4. Columns’ horizontal deformation without shallow layer

A stress point at plastic state is called plastic point which is used to demonstrate failure points under Mohr-Coulomb failure criteria (Brinkgreve & Broere, 2008). Figure 5 shows plastic points’ position for individual columns with 200 kPa of \(q_u\) value. The failure points appear on the bottom as well as the middle columns while no failure point is observed in the columns with \(q_u = 5,000\) kPa even at large deformation. It is obvious that the deep mixing columns experience an internal failure with small \(q_u\) value but show an external failure with high value of \(q_u\). This observation agrees well with the previous research result (Kitazume & Maruyama, 2006) and (Kitazume & Maruyama, 2007).

Fig. 5. Plastic points \((q_u = 250\) kPa, 160 kPa embankment’s pressure.

4.2 Failure pattern with shallow mixing layer

The effect of shallow mixing layer on the failure pattern of deep mixing columns is investigated. The thickness of shallow mixing layer is changed from 2 m to 10 m with different strength of mixing material.

The embankment pressures at yield in these cases are plotted in Fig. 6. In the figure, the vertical axis indicates the thickness of shallow mixing layer while the horizontal indicates embankment pressure at yield. The result confirms that the thickness of shallow mixing layer has strong effect on embankment pressure at yield especially with small \(q_u\) value.

Fig. 6. Embankment pressure at yield with various shallow layer thickness

By turning to columns’ deformation, the horizontal displacements of the most-rear column are observed in Fig. 7. From Fig. 7(a), columns with 200 kPa of \(q_u\) value experience mostly the same displacement but the shallow mixing layer part displacement is reduced by...
increasing its thickness. The thicker the shallow mixing layer is, the less bending the column is observed. Figure 8(a) shows the appearance of plastic points with shallow mixing layer strength, \( q_u = 250 \) kPa which focuses on the bottom and the connecting position between column and shallow mixing layer at 170 kPa of loading.

On the other hand, although the most-rear columns with \( q_u = 5,000 \) kPa has small bending, large sliding deformation is observed (Fig. 7(b)). However, a few failure point is observed in mixing area with \( q_u = 5,000 \) kPa under 230 kPa of embankment pressure as can be seen in Fig. 8(b). Therefore, bending failure may not be considered as the main reason for the failure of the column and shallow mixing layer area, but large sliding deformation should be taken into account.

### 4.3 Discussion on failure mechanism

(a) Internal failure

In the case of improved ground without shallow mixing layer, individual column experiences bending failure with failure positions focusing at bottom as well as at middle of each columns based on plastic points’ position in Fig. 5. These columns are clock-wise bending which is well agreed with one of the possible failure modes of single columns proposed by B.B Broms (Moseley & Kirsch, 2004). However, the clockwise bending in this study may not agree with the counter clockwise bending of deep mixing columns which is done by Kitazume & Maruyama (2007). It may due to different strength and stiffness of the clay layer around deep mixing columns.

When a shallow mixing layer is applied, deep mixing columns experience tilting deformation and bending failure at the connecting position between columns and shallow mixing layer confirmed by appearance of failure points as shown in Fig. 8 for \( q_u = 250 \) kPa.

(b) External failure

With high strength mixing material, individual columns tilt counter-clockwise at the final loading step. No plastic point observed in individual columns as well as a few failure point appearing in columns with shallow layer (Fig. 8(b)) confirms an external failure of columns with \( q_u = 5,000 \) kPa. This failure mechanism is well agreed with the external failure which is observed by the centrifuge experiments (Kitazume & Maruyama, 2006). However, the deformation of columns in Fig. 7(b) confirms a sliding failure which is taken place in 5,000 kPa columns irrespective of thickness of shallow mixing layer except no shallow mixing layer. As a
result, in term of external failure pattern, the tilting failure of individual columns is replaced by a sliding failure when deep mixing columns are reinforced by a shallow mixing layer.

4.4 Effect of shallow mixing layer thickness

The degree of the decrement in horizontal displacement at embankment toe is evaluated by a displacement ratio. It is defined as the ratio of horizontal displacement at toe of embankment between with shallow mixing layer and without shallow mixing cases. The smaller this ratio is, the more displacement reduces. Figure 9 shows the effect of shallow mixing layer thickness on horizontal displacement with 4 different values of \(q_u\). In the figure, the horizontal displacement decreases with increment of thickness of shallow mixing layer irrespective of \(q_u\) values. Similarly, the decrement of horizontal displacement is greater with higher value of unconfined compressive strength of mixing material irrespective of thickness of shallow mixing layer.

A strong decrement in horizontal displacement about 80% is observed with \(q_u = 5,000\) kPa even with very thin layer of shallow mixing layer. However, the effect of thickness of shallow mixing layer is not significant with high strength mixing material. When \(q_u\) is relatively small, the horizontal displacement gradually decrease with increasing of shallow mixing layer.

The effect of shallow mixing layer on the embankment pressure at yield is shown in Fig. 10. From the figure, increasing thickness of shallow mixing layer leads to a greater embankment pressure at yield irrespective of mixing material properties. However, the effect of shallow layer thickness with low strength columns is greater than that with high strength columns.

5 CONCLUSION

Without shallow mixing layer, sliding is not the main mechanism of columns’ deformation. Bending failure pattern should be considered for low strength columns as internal failure mechanism. With high strength mixing material, tilting pattern is the main mechanism for columns’ deformation.

When using shallow layer, columns are bent and fail at connecting position when increasing shallow mixing layer thickness in term of internal failure with low strength columns. In term of external failure, tilting failure without shallow mixing layer is replaced by sliding pattern when increasing shallow layer thickness.

Shallow mixing layer has significant effect on horizontal displacement as well as embankment pressure at yield especially for high strength columns. However, the effect of thickness of shallow mixing layer on horizontal displacement is not considerable in term of external stability.

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