EVALUATION OF CONSTRAINT EFFECT OF DMM WITH VARIED SHAPE AND ARRANGEMENT OF STABILIZED BODIES USING CENTRIFUGE MODEL TEST

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ABSTRACT: In order to evaluate the constraint effect of the different shape and arrangement of the stabilized bodies, four cases of centrifuge model test under 80G were carried out as follows. Case0: no countermeasure, Case1: square arrangement of column shape, Case2: wall shape, Case3: closed flat tubular shape. Case0 was the reference test for the purpose of evaluating the strength deformation characteristics of the soft ground. The height of the embankment was 7m for the Case0 and 10m for other cases respectively. Failure occurred in Case0 and different behaviours were observed among other three cases even though the improvement ratio was the same.

INTRODUCTION

Actual behaviour of the improved ground is varied with the variations of the shape and arrangement of the stabilized bodies even if the improvement ratio is the same. As the conventional ground improvement design methods don't take into account the effect that the ground is constrained by the stabilized bodies and so on, an innovative new method shall be developed by considering above mentioned effect.

In order to evaluate the constraint effect of the different shape and arrangement of the stabilized bodies, four cases of centrifuge model test were carried out.

Observed behaviours were quite different even though the improvement ratio was the same.

These different behaviours seemed to reflect the variation of constraint of unimproved ground by the stabilized bodies. Authors investigated how to take into account these effects in the case of designing ground improvement.

CENTRIFUGE MODEL TESTS

Mid-sized centrifuge apparatus used for this research belongs to Public Works Research Institute. This apparatus is shown in Photo 1 and its specifications are summarized in Table 1.

Embanking model tests were carried out with the centrifugal force of 80G. Thus the model scale was 1/80. Typical centrifugal model for improved ground is shown in Fig.1. SS means Surface Stabilization and DMM means Deep Mixing Method respectively. Unconfined compressive strength of both was 1000kN/m².

Table 1 Specifications of the centrifuge apparatus

| Effective rotation radius | 3.5m |
| Maximum centrifugal force | 140G |
| Maximum loading capacity  | 140t·G |

Table 2 Description of the centrifuge tests

<table>
<thead>
<tr>
<th>Case</th>
<th>Shape of stabilized body</th>
<th>Prototype Embankment height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Unimproved</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>Column</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Wall</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Flat tubular</td>
<td>10</td>
</tr>
</tbody>
</table>

Fig. 1 A typical centrifugal model for improved ground case
Zircon sand (γₖ=31.2kN/m³) was used for embankment. This means that the height of the prototype embankment illustrated in Fig. 1 corresponds to 10m.
Tests carried out are briefly described in Table 2. The improvement ratio of DMM of Case 2-4 was around 8% of embanking area.
Test procedure is as follows.
1) Double layered rubber membrane with silicone grease was used to reduce the friction between ground and wall of the rigid container.
2) The container was filled with slurry kaolin clay on the dense sand layer with using vibrator.
3) Brass rods were placed on the clay in order to obtain the specified strength.
4) Clay was consolidated with 80G.
5) Unload centrifugal load and remove brass rods.
6) Small markers were placed on the top surface and the side of the clay.
7) Clay were replaced with stabilized bodies for Case 2-4.
8) Laser displacement transducers were placed.
9) Reconsolidation under centrifugal force was carried out.
10) Embanking was simulated by using sand hopper with opening the shutter at the bottom [1-3].
11) Deformation and so on were measured about 6000s which corresponds to more than one year of prototype.
12) After unloading the centrifugal force, zircon sand was removed and the displacements of surface markers were measured.
13) For the case 2-4, the cracks of the SS layer were sketched and clay ground was excavated to observe the situation of stabilized bodies.

The items measured during centrifugal loading are illustrated in Fig. 2. The pore pressure transducers were mounted in the sidewall of rigid container. The earth pressure transducers were set on the SS layer just above the DMM stabilized bodies. The other earth pressure transducers were set at the bottom of the SS layer to measure the pressure of unimproved clay. One of the earth pressure transducer for unimproved clay was located outside of stabilized body only in Case 4. Displacement at the toe was measured by laser displacement transducers. DV represents vertical displacement and DH shows horizontal displacement respectively.

In addition, authors intended to measure the strain of the stabilized bodies of DMM. However, as the calibrated load strain curves were not linear enough, the measured values were used to suppose the behaviour of the stabilized bodies.

The shape and arrangement of the stabilized bodies of Case 2-4 are shown in Table 3.

<table>
<thead>
<tr>
<th>Case</th>
<th>Shape and arrangement of stabilized bodies</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td><img src="image1" alt="Image" /></td>
</tr>
<tr>
<td>3</td>
<td><img src="image2" alt="Image" /></td>
</tr>
<tr>
<td>4</td>
<td><img src="image3" alt="Image" /></td>
</tr>
</tbody>
</table>

**Table 3 Description of the centrifuge tests**

**TEST RESULTS**
A circular slip failure occurred at about 70-80% of the final height of embankment in Case 1. This meant that the undrained strength of the Kaolin clay must be appropriate because the safety factor of circular slip for this case was 0.62. Photo 2 shows the slip failure of case 1. Another cases did not show apparent failure. The safety factor of other case was around 1.1.

![Photo 1 Slip failure occurred in case 1](image4)

**Final Deformation**
Contours of settlement of the markers on the ground surface (on the SS layer and Kaolin clay) after unloading centrifugal force are shown in Table 4. The numbers in legend shows the displacement in model scale.

Because of the slip failure, Case 1 shows significant uplift in front of the slope. Note that the size of the embankment was smaller than other case.

Among the improved cases, the settlement of Case 4 is obviously smaller than other two cases.
The deformation in front of the toe of the slope is shown in Table 5. Case 1 shows the typical failure pattern. The deformation is much smaller for improved case. However, Case 2 shows greater deformation than case 3 and 4. The difference of resulting deformation derives from the difference of constraint effect of the stabilized bodies. Namely, Case 4 shows the higher effect than Case 2 and Case 3. These results are summarized in Fig. 3. Each deformation shows an averaged value. In this Figure, the value is shown in prototype scale. Even though the improvement ratio of all cases are the same (around 8%), the observed settlement and deformation of each case were quite different. Settlement of the case 2 and case 3 are almost same and that of case 4 is about 70%. Horizontal deformation at the toe of the slope of case 3 and case 4 is less than 1/5 of case 2.

The situation of stabilized bodies were as follows. Case 2: Many of them were inclined and got broken. Case 3: Several vertical clacks were observed. Case 4: There was no damage.

**Behaviour during Centrifugal loading**

Vertical deformation measured by laser displacement transducer is shown in Fig. 4. Both Case 1 and Case 3 heaves just after embankment load. However, all cases continue to settle down up to 6000s.

Meanwhile, measured excess pore pressure is shown in Fig. 5. High pressure was measured just after embankment loading then it was decreasing and seemed to become stable at about 5000s except Case 1.
3D FEM ANALYSIS
In order to simulate the centrifuge model test results, three dimensional elasto-plastic FEM was carried out. The constitutive model was Mohr-Coulomb. Input parameters are listed in Table 6. For the analysis, prototype scale was used.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( \gamma_s ) (kN/m(^3))</th>
<th>c (kN/m(^2))</th>
<th>( \phi ) (°)</th>
<th>( \psi ) (°)</th>
<th>E (MN/m(^2))</th>
<th>v</th>
</tr>
</thead>
<tbody>
<tr>
<td>Embankment</td>
<td>19</td>
<td>0</td>
<td>35</td>
<td>15</td>
<td>5</td>
<td>0.3</td>
</tr>
<tr>
<td>Soft Clay</td>
<td>16</td>
<td>9.3+1.56Z</td>
<td>0</td>
<td>0</td>
<td>0.6</td>
<td>0.49</td>
</tr>
<tr>
<td>SS, DMM</td>
<td>16</td>
<td>500</td>
<td>0</td>
<td>0</td>
<td>150</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Note: \( Z \) represents the depth from the surface.

Parameters for embankment were assumed. Parameters for soft clay were determined by CU test. Tensile strength of SS and DMM was assumed 20% of compressive strength.

Young's modulus for soft clay was determined by 10% order secant modulus. Deformed mesh at the final height of Case 1 is shown in Fig. 6. Circular slip failure is also observed in numerical model.

Comparison of computed displacements and observed values is shown in Fig. 7. FEM results showed similar absolute value of settlement under crown. However, less constraint effect is observed in Case 4. Horizontal displacement at toe is much smaller than observed value in case 2 and showed little difference among three cases. Regarding settlement at toe, the tendency is completely opposite. Further investigation is needed to achieve better simulation.

CONCLUSIONS
Significantly different behaviours were observed with varied shape and arrangement of stabilized bodies by centrifuge model tests. Deformation was effectively controlled by choosing the shape and arrangement which could constrain unimproved soil. However, 3D elasto-plastic FEM could not simulate this effect sufficiently. Further investigation is needed to evaluate this effect by numerical analysis.

ACKNOWLEDGEMENT
Authors highly acknowledged Mr Kohashi and Mr Tsutumi in Public Works Research Institute where centrifuge model tests were carried out. Also authors appreciate Mr Kimura and Mr Narushima who were in charge of Centrifuge model tests.

Japanese patent has been issued regarding the idea for realizing constraint effect in ground improvement and pending in several countries. CGI circle Japan is a group to establish a design method for ground improvement considering constraint effect. Authors thank for receiving many ideas from the members.

REFERENCES