STABILITY OF TRENCH EXCAVATION UNDER CONSTRUCTION MACHINERY LOAD

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ABSTRACT
Trench collapse causes a considerable number of deaths and injuries of workers every year in Japan. In this paper, a series of centrifuge modelling was conducted in order to examine the stability of trench excavation under the construction machinery load. The NIIS in-flight excavator was used to simulate the trench excavation process during the centrifuge test. In addition, the effects of ground condition, magnitude and location of the construction machinery load on the failure mechanism were also investigated. The centrifuge test results clearly revealed that the mechanism of failure was mainly controlled by the magnitude of the machinery load and the bearing capacity of ground.

1. INTRODUCTION
There are many labor accidents in which the workers are killed and buried under collapsed ground when the construction machinery such as a drag shovel falls or topples over the edge of the trench during excavation. Photograph 1 shows the example of the ground collapse during the trench excavation. Based on the labor accident reports, during the period of 1994 to 2002, there were approximately 30 workers killed every year in Japan due to this type of failure. To prevent the loss of life and injury caused by the ground collapse, it is necessary to gain more understanding about the effect of construction machinery load, geometry of ground excavation (e.g. slope angle and excavation depth) and characteristic of ground strength on the stability of trench excavation. Geotechnical centrifuge modelling is commonly accepted as a powerful tool for studying a wide range of geotechnical problems. The stability and failure mechanism of ground excavations have been investigated using the centrifuge modelling by many researchers (Kusakabe 1982, Taylor 1984 and Toyosawa et al. 1994). However, the stability and failure mechanism of trench excavation under the construction machinery load have not been fully investigated. Therefore, in this paper, a series of centrifuge modelling tests was conducted on various types of ground models under different magnitudes and locations of the machinery load in order to examine the stability and the failure mechanism of trench excavation under the construction machinery load.

2. CENTRIFUGE MODELLING
In this paper, a series of centrifuge tests was performed using the Mark-II centrifuge in the centrifuge test laboratory of the National Institute of Industrial Safety (NIIS). The NIIS Mark-II centrifuge has an effective radius of about 2.3 m with a maximum acceleration of 100g and 50g under the static and dynamic conditions, respectively. The detail of the NIIS Mark-II centrifuge was described by Hori et al. (2006). The centrifuge tests were conducted on ground models at the centrifuge acceleration of 30g and test results were presented in the model scale.
2.1 Modelling of Construction Machinery Load

Figure 1 shows a schematic illustration of the drag shovel which is commonly used in trench excavation, the geometry of the drag shovel such as a full width of vehicle or crawler (B), a width of wheel (b) and a side clearance from the slope crest (S) are also presented in the figure. Based on the investigation of 287 different types of the drag shovels used in the trench excavation, the specifications of the drag shovel including the vehicle width, the width of wheel and the bearing pressure of the wheel can be characterized as shown in Figures 2 and 3. The bearing pressure of wheel or crawler is in the range of 9.8 to 118 kPa. Figure 2 shows the proportion of the drag shovel by the width of wheel, b. It was found that the width of wheel distributes in the range of 0.4 to 1.27 m and approximately 50% of the drag shovels have the width of wheel of 0.6 m. Figure 3 shows the proportion of the drag shovel by a ratio of the vehicle width and the width of wheel, B/b. As can be seen in the figure, about 83% of the drag shovels have the vehicle width of about 5 times of the width of wheel. Therefore, in this paper, the construction machinery load was modelled by a rigid block (U-shape) with b = 0.6 m (in prototype scale) and B/b = 5 as shown in Figure 4. It should be noted that the machinery load was modelled under the static condition.

2.2 Ground Model Preparation

The ground model was prepared in a rigid model box (internal dimensions of 100 mm in width, 450 mm in length and 272 mm in height) with a transparent Plexiglas front wall in order to provide side viewing of the ground model during the centrifuge test. The membrane was attached onto the ground model and silicone grease was smeared between the sidewall of model box and the membrane to reduce the sidewall friction. Three different kinds of ground models were prepared, namely, uniform sand ground model (model A), layered sand ground model (model B) and Kanto loam (a volcanic cohesive soil in Japan) ground model, (model C). The preparations of the ground models are described as follow.

Ground model A: the uniform sand ground model was prepared by pluviating air-dried Toyoura sand from a sand hopper through air at a controlled drop height into the rigid model box. Toyoura sand is classified as a uniform clean fine sand with a mean grain size, $D_{50} = 0.18 \text{ mm}$ and a density of soil particle, $\rho_s = 2.65 \text{ g/cm}^3$. By this method, homogeneous dense sand ground model with a relative density, $D_r$ of about 78% was obtained. The ground model was saturated by soaking the ground model in the water for about 24 hours. After the saturation process, the water content, $w$ of the ground model of 21.6% was obtained. In order to examine the degree of saturation, $S$ and the water content of the ground model at the centrifuge test condition (at acceleration of 30g), the ground model was placed onto the centrifuge swinging platform and the centrifuge acceleration was gradually increased to the acceleration of 30g. It was found that the degree of saturation and the water content decreased with time and the water content and the degree of saturation remained unchanged after 15
minutes \((w = 3.2\%, \ S = 15.2\%)\). The density of the ground model was about 1.620 g/cm\(^3\). After the centrifuge test, the water content was measured at every 5 cm depth from the ground surface and uniform value of the water content was observed.

Ground model B: the layered sand ground model was prepared by the same material and method as used in the ground model A. However, after pluviating Toyoura sand into the model box to a thickness of approximately 10 mm, the pouring hole of the sand hopper was closed. The ground surface was levelled and the colored-dyed Toyoura sand was then placed on the ground surface with a thickness of about 5 mm in order to highlight the deformation and the location of failure surface. Thereafter, the pouring hole was reopened and the next ground layer was prepared using the same method described above. The water content and the degree of saturation of the ground model were consistent well with that of the ground model A, and the density of the layered sand ground model after the test was about 1.605 g/cm\(^3\).

Ground model C: the Kanto loam with the particle size passing the 2 mm sieve was used in this ground model. The water was sprayed and mixed with the Kanto loam to provide the conditions of optimum water content in advance. The ground model was placed into the model box and compacted under a pressure of 49 kPa by the bellofram cylinder. For the first ground layer with a thickness of about 70 mm, the Kanto loam of 2500 g was compacted for 30 minutes. For the next ground layers, the Kanto loam was compacted in layer of about 7.5 mm thick for a total of 18 layers. After each compaction, a thin layer of air-dried kaolin powder was placed on the ground surface for the observation of the failure surface. By this method, the relative density, the wet density, and the water content of the ground model were about 66 \%, 119\% and 0.928 g/cm\(^3\), respectively. After completion of the preparation of ground models, the construction machinery load model was then placed on the top of the ground surface at the specific location. The typical experimental model is shown in Figure 5.

2.3 Characteristics of Ground Models

In order to evaluate the strength of the ground models, the small-sized cone penetration test and the bearing capacity tests were conducted in the centrifuge test. The small-sized cone penetrometer has a diameter of 5 mm with a base area and a tip angle of 0.196 cm\(^2\) and 60 degrees, respectively. Figure 6 shows the cone penetration test results for the ground model A, B and C, the cone resistance increased linearly with depth and centrifuge acceleration level for the uniform sand (model A) and the layered sand (model B) ground models. It should be noted that the test result was presented corresponding to the model scale. As expected, the ground model B has a lower cone resistance than that of the ground model A for a given centrifuge acceleration. This is mainly due to the weakness of the colored sand layers. In contrast, in case of Kanto loam ground model (model C), the uniform ground strength can be observed in which slope of the cone resistance-depth curve drop at the depth of about 20 mm and the cone resistance remains unchanged with depth. In addition, the cone resistance of the ground model under the 1g gravity field and the centrifuge acceleration of 30g are almost identical.
of 30g. The test results for the ground model A, B and C are presented in Figure 7, the bearing capacity, $q$ is plotted with the normalized settlement, $S_m / B_m$. As can be seen in the figure, the ultimate bearing capacity of 1230 kPa and 700 kPa are observed in the ground model A and B, respectively. It is obvious that the ground model C has the lowest ultimate bearing capacity (91 kPa) when compared with the other ground models.

Figure 7. The bearing capacity test results

2.4 Test Conditions

A series of centrifuge tests was conducted on the three different ground models under different magnitudes and locations of the construction machinery load. The test conditions are summarized in Table 1. In addition, the centrifuge tests were also conducted on the ground models without the machinery load for the comparison.

Table 1. Summary of the test conditions

<table>
<thead>
<tr>
<th>Ground model</th>
<th>b (mm)</th>
<th>Bearing pressure (kPa)</th>
<th>S/b</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20</td>
<td>35.4</td>
<td>0.5, 0.75, 1.25, 1.75</td>
</tr>
<tr>
<td>B</td>
<td>20</td>
<td>35.4</td>
<td>0.5, 0.75, 1.25, 1.75</td>
</tr>
<tr>
<td>C1</td>
<td>20</td>
<td>35.4</td>
<td>1.25</td>
</tr>
<tr>
<td>C2</td>
<td>20</td>
<td>91.7</td>
<td>0.5, 0.75, 1.25, 1.75</td>
</tr>
</tbody>
</table>

As can be seen in the Figure 7 and the Table 1, the bearing pressure of the machinery load (35.4 kPa) is small very about 3% and 5% of the ultimate bearing capacity of the ground model A and B, respectively. While in the ground model C1, the bearing pressure of the machinery load is about 40% of the ultimate bearing capacity. In order to see more clearly the influence of the bearing pressure on the stability of trench excavation, the machinery load model with the bearing pressure of about the same as the ultimate bearing capacity of ground was used in the model C2.

Photograph 2. Ground model B after failure, (a) without machinery load, (b) with machinery load $S = 0.5b$ and (c) with machinery load $S = 1.25b$

2.5 Test Procedures

After completion of the experimental model setup, the ground model was loaded onto the centrifuge swinging platform and the centrifuge acceleration was then increased gradually until the acceleration of 30g. The NIIS in-flight excavator (Toyosawa et al. 1998), which is
capable of excavating the ground model during the high centrifuge acceleration environment was used in this paper for simulating the trench excavation process. After the centrifuge acceleration reached 30g, the ground model was excavated vertically with a thickness of about 5 mm until the ground failure can be observed. The excavation depth at just before the ground failure was recorded and defined as the maximum excavation depth.

**Figure 8. Relationship between the maximum excavation depth and the side clearance, S/b**

3. **EXPERIMENTAL RESULTS**

3.1 Failure Mechanism of Sand Ground

Photograph 2(a) shows the cross-section of the ground model B after the failure in case of no machinery load, and photographs 2(b) and (c) are the example of the failure pattern of the ground model B under the machinery load. The failure pattern of ground model A is identical with that of the ground model B even the photographs are omitted here. It is obvious from the photographs that the failure mechanism is mainly due to the instability of slope. This may be attributed to the fact that in case of the sand ground models (models A and B) the bearing pressure of the machinery load is relatively small when compare to the ultimate bearing capacity of ground. Therefore, the self-weight of ground plays the important role on the instability of slope.

Figure 8 shows the relationship between the maximum excavation depth and the normalized side clearance, S/b of the ground model A, B and C2. The maximum excavation depths of the ground model A and B in case of no machinery load are 83 mm and 58 mm, respectively. It is apparent that the maximum excavation depth increases with the side clearance in the ground model A and B. However, when the side clearance is more than 1.25b, the influence of the side clearance on the maximum excavation depth seems to be insignificant in which the maximum excavation depth under the machinery load is almost the same as in case of no machinery load.

3.2 Failure Mechanism of Kanto Loam Ground

Photograph 3(a) shows the failure pattern of the ground model C1 in case of no machinery load. The maximum excavation depth of about 220 mm was observed after the failure. Photograph 3(b) shows the failure pattern of the ground model C1 under the machinery load. The bearing pressure of the machinery load is about 40% of the ultimate bearing capacity of ground. The machinery load model was hung with the iron wire in order to prevent the damage of the failure pattern due to the falling of machinery load model after the failure. The maximum excavation depth of about 180 mm was observed at S = 1.25b. By comparing the photographs 3(a) and (b) the failure patterns of the ground model C1 with and without the machinery load are almost identical. In addition, the mechanism of failure is similar to that of the sand ground models in which the instability of slope is a major cause of failure. On the other hand, in case of ground excavation under the machinery load with the bearing
pressure equal to the ultimate bearing capacity of ground (model C2), the failure mechanism is totally different as can be observed in Photographs 4(a), (b) and (c).

Figure 9 shows the schematic illustrations of the failure mechanism observed in the ground model C2. The failure mechanism was initiated by the collapse of ground beneath the machinery load due to the insufficient of ground bearing capacity, and the surrounding ground was then pushed towards the excavation face. It was considered that the failure mechanism was similar to the bearing capacity failure of foundation. The increase in the maximum excavation depth with the side clearance of the ground model C2 can be observed in the Figure 8.

It should be noted that at the side clearance of 1.75b, the maximum excavation depth is only about 50% of that observed in case of no machinery load (maximum excavation depth of 220 mm). This indicates that the influence of the side clearance on the maximum excavation depth is more significant in the ground model C2 than the ground model A and B.

4. CONCLUSIONS

The size and magnitude of the construction machinery load were modelled according to the investigation of drag shovel specifications. The failure mechanisms of trench excavation under the construction machinery load are different depending on the magnitude of bearing pressure of the machinery load and the ultimate bearing capacity of ground. When the bearing pressure of the machinery load was smaller than the ultimate bearing capacity of ground, the failure mechanism was mainly due to the instability of slope. On the other hand, when the bearing pressure was approximately equal to the bearing capacity of ground, the failure mechanism was similar to the bearing capacity failure of foundation and the effect of the side clearance on the maximum excavation depth was highly significant. In addition, because the construction machinery usually operates under the dynamic condition, further research should be conducted to examine the stability of trench excavation under the dynamic load.

References


