CENTRIFUGE MODEL TESTS ON A COHESIVE SOIL SLOPE UNDER EXCAVATION CONDITIONS

MING LI, GA ZHANG, JIAN-MIN ZHANG and C. F. LEE

ABSTRACT

Problems induced by slope excavations are quite common. An in-flight excavation device was realized to simulate the live excavation of slopes at high g levels during centrifuge model tests. A series of centrifuge model tests was conducted to simulate the excavation of a slope at different inclinations and heights, and the effect of the excavation size was taken into consideration. The displacement histories of points over the slope were measured by an image capture and displacement measurement system. Measurement results showed that the excavation-induced deformation process could be divided into several phases with different displacement distribution features. The excavation was found to only affect a restricted zone of the slope whose boundary could be outlined by an A-surface. A strain analysis was conducted to determine the excavation-induced strain localization area of the slope. The degree of strain localization increased as the excavation time increased, but the width of the strain localization area was nearly invariable. Shear failure first occurred near the excavation surface and then extended upwardly to the slope surface under excavation conditions, while tension failure played a dominant role in the upper part of the slip surface. The strain localization area moved towards the slope surface with an increasing slope inclination. The lower part of the final slip surface was located in the strain localization area.

Key words: centrifuge model test, excavation, influence zone, progressive failure, slope (IGC: D6/E6/E14)

INTRODUCTION

Excavations are conducted frequently in slope engineering, such as highway slopes, embankments and foundation pits. Unfortunately, excavations have also been the major cause of slope failure, leading to severe economic repercussions and the loss of life. The stability of a slope under excavation conditions needs to be properly evaluated, as the failure features of the excavated slope may be significantly different from those of other loading styles.

The limit equilibrium method has often been adopted to analyze the stability of excavated slopes. For example, the safety level of a large-scale mass in a cut limestone slope along a highway route was evaluated using the simplified Bishop method (Oztekin et al., 2006). And, a type of limit equilibrium method was revised to consider an evolution process for the failure of a slope (Miao et al., 1999). More rigorous numerical methods have also been used to investigate the deformation and the failure of slopes during excavation. The excavation-disturbed zones of a large rock excavation and permanent shiplock slopes in the Three Gorges Project were determined, respectively, on the basis of a nonlinear finite element analysis.

The zones were generally found to be similar to those obtained from the monitoring data (Deng et al., 2001; Sheng et al., 2002). Sabatini and Finno (1996) used the finite element method to simulate strain localization, restricted to a band in clay, through a comparison with test observations.

A few case studies have been conducted on the excavation-induced failure of slopes (e.g., Yamanouchi et al., 1980; Thomson and Kjartanson, 1985; Yamaguchi and Shimotani, 1986; Yamada et al., 1987). Such prototype observations can provide firsthand information, which is extremely valuable to researchers, although the data are often not comprehensive enough for a thorough investigation of the failure mechanisms. Cooper et al. (1998) injected water into an excavated slope to accelerate the failure process. It was found that local failure first appeared at the slope toe, and then a tension crack occurred successively in the slope crest. The results of the excavated slope observations were used for a back analysis to determine the strength parameters of soft Bangkok clay (Boonsinsuk, 1995). Disastrous accidents can also be reduced by monitoring the warning signs at the early stages (e.g., Yamaguchi and Shimotani, 1986).

Centrifuge model tests have provided an effective ap-
proach for investigating the behavior and failure mechanisms of slopes under different conditions, because they can provide the same stress level for the model and the prototype (e.g., Schofield, 1980; Indrasenan et al., 2006; Viswanadham and Mahajan, 2007; Sommers and Viswanadham, 2009; Hu et al., 2010; Wang et al., 2010).

A few types of methods have been used to simulate excavations in centrifuge model tests (Kimura et al., 1993). Several types of centrifuge model tests have been conducted on slopes pre-excavated at the 1-g level, which had a significantly different stress path from the actual cases (e.g., Davies and Jones, 1998). Tamrakar et al. (2006) improved an in-flight excavator and conducted three types of slope excavation tests, focusing on the maximum critical excavation height. Failure patterns for the slope after the excavation were also observed through captured images. Systematic centrifuge model tests have yet to be conducted to analyze the mechanisms of deformation and the failure of slopes under excavation conditions.

In this paper, a series of excavation centrifuge model tests is conducted to investigate the deformation and failure behavior of excavated slopes. The objectives of this paper are: (1) to describe a device to simulate slope excavations during centrifuge model tests, (2) to conduct a series of slope excavation tests using a centrifuge, (3) to summarize the fundamental rules of behavior for slopes during excavations, and (4) to analyze the excavation-induced failure process of slopes on the basis of displacement measurements.

**DEVICE**

A device was realized to simulate the excavation of a slope in-flight on the basis of the centrifuge at Tsinghua University (Figs. 1 and 2). The capacity of the centrifuge is 50 g-ton and the maximum acceleration is 250 g. This excavation device was installed on a model container, 50 cm long, 20 cm wide and 35 cm high. One side of the model container was equipped with transparent organic glass through which the slope could be observed.

The excavation simulator consisted mainly of a steel blade, two electric motors, two aluminum alloy platforms and a group of rails with sliders (Fig. 2).

The steel blade was used to cut part of the soil from the slope toe and push it away. The steel blade is 19.5 cm in width, 15 cm in height and 0.5 cm in thickness. The profile of the blade was designed with a U-shape in the horizontal section to increase rigidity and to prevent the

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**Fig. 1.** Photograph of excavation simulator for centrifuge tests

**Fig. 2.** Structural view of excavation simulator for centrifuge tests (Unit: cm)
cut soil from dropping from the sides of the blade (Fig. 3). The edges of the bottom and the sides of the blade were made as single wedges to decrease the cut resistance and disturbance to the slope. The steel blade was vertically connected to a motor shaft (Fig. 2(a)), and its strength and rigidity can guarantee the design functions.

The blade is capable of carrying out two basic actions, namely, “cut” and “push”, through the use of two electric motors, respectively. The combination of these actions achieves the excavation that cuts the soil and pushes it away from the slope.

The “cut” action is realized by a 140-W vertical DC motor. The DC electric motor, whose shaft can move up and down vertically, is located in the middle of the upper platform (Fig. 2). The motor, with a reducer system, can provide a force of over 15 kN in the vertical direction, which satisfies the requirements of the excavation test at the 50-g level. A brake is equipped in the DC electric motor in order to hold the position of the shaft when the electric motor is switched off.

The “push” action is realized by a horizontal AC motor, which drives the upper platform, including the blade, to move horizontally. This 120-W AC electric motor is fixed on the left side of the lower platform on the top of the model container; it can output a force of 20 kN via a two-stage speed reduction gear. There is also a brake in this elector motor to hold the position of the rack when the motor is switched off. The upper platform can move smoothly along the lower platform through the four flange sliders of the guide-ways. It should be noted that the guide-way has a few advantages such as high-precision, low noise level, low frictional factor and high parallelism. Each slipper block can sustain a bending moment of 0.15 KN·m.

The excavation is controlled by switches and an image-capture system. The excavation can be observed through the transparent organic glass side of the model container using the image capture system. A two-dimensional coordinate is drawn on this transparent side to accurately control the excavation process. The switches are connected to the two electric motors by a slip ring on the centrifuge; thus, the actions of the blade can be started or stopped according to the observations made during the excavation process.

The excavation procedure can be summarized as follows: (1) The steel blade is pushed horizontally to the given position and moves vertically down into the slope. (2) The steel blade is pushed to cut soil away from the slope. (3) The steel blade is driven up and pulled to its original position for the next excavation.

TESTS

Model

The soil used in the tests is a type of silty clay taken from a subway station in Beijing, China. The plastic limit and the liquid limit are 15% and 28%, respectively. The plastic index is 13 and the specific gravity is 2.71. The soil, which had a water content of 18%, was compacted to a dry density of 1.5 g/cm³ by horizontal layers, 4 cm thick, in the model container. Drained triaxial tests were conducted on the soil (Fig. 4). It can be seen that the deviation stress increased with an increasing axial strain. The shear strength parameters were determined, with cohesion of 17 kPa and an internal friction angle of 28.5°.

Final slopes were obtained by cutting out the redundant soil. All slopes were 25 cm high, equivalent to 12.5 m high in prototype at a level of 50 g. A horizontal soil layer (ground), 3 cm high, was maintained under each slope in order to reduce the influence of the bottom of the container on the deformation of the slopes. Silicone oil was smeared between the slopes and the sides of the model container to decrease friction. Figure 5 shows a typical slope model for the centrifuge model tests.

Schemes

This paper focuses on the failure process of cohesive slopes due to excavations. The influence of slope height (simulated using different g levels in the tests), slope inclination and excavation size were also investigated through a series of centrifuge model tests. Table 1 lists the cen-

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**Fig. 3. Steel blade of excavation simulator**

**Fig. 4. Results of drained triaxial tests on soil. \( \sigma_1 \): maximum principal stress, \( \sigma_3 \): minimum principal stress, \( \varepsilon_1 \): axial strain**
Table 1. List of centrifuge model tests

<table>
<thead>
<tr>
<th>No.</th>
<th>g level</th>
<th>Slope height at model dimensions (cm)</th>
<th>Slope height at prototype (m)</th>
<th>Slope inclination (V : H)</th>
<th>Excavation height at model dimensions (cm)</th>
<th>Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>50</td>
<td>25</td>
<td>12.5</td>
<td>1.2:1</td>
<td>8</td>
<td>Y</td>
</tr>
<tr>
<td>#2</td>
<td>50</td>
<td>25</td>
<td>12.5</td>
<td>1.2:1</td>
<td>4</td>
<td>N</td>
</tr>
<tr>
<td>#3</td>
<td>30</td>
<td>25</td>
<td>7.5</td>
<td>2:1</td>
<td>8</td>
<td>N</td>
</tr>
<tr>
<td>#4</td>
<td>30</td>
<td>25</td>
<td>7.5</td>
<td>1:1</td>
<td>8</td>
<td>Y</td>
</tr>
<tr>
<td>#5</td>
<td>50</td>
<td>25</td>
<td>12.5</td>
<td>1:1</td>
<td>8</td>
<td>Y</td>
</tr>
<tr>
<td>#6</td>
<td>50</td>
<td>25</td>
<td>12.5</td>
<td>1.5:1</td>
<td>8</td>
<td>Y</td>
</tr>
</tbody>
</table>

Procedure

After completing the model, the excavation device was installed and the model container was put into the centrifuge. The centrifugal acceleration was slowly increased to the scheduled g level and then maintained. The excavation was conducted until the settlement of the slope, due to the increase in centrifugal acceleration, became steady. The image-capture and displacement-measurement system was used to record the images and to measure the displacement of the slope during the excavation.

DEFORMATION PHASES

Figure 6 shows photographs and displacement contours of the slope at different excavation times (test #1). Here, the excavation time is the accumulated time from the moment at which the cut soil is taken away from the slope. It can be seen that the displacement of the slope, in both horizontal and vertical directions, increased with an increasing excavation time. The final landslide occurred at an excavation time of 25.6 s; the slip surface is outlined in Fig. 7(a).

The deformation process can be divided into several phases with different features of displacement distribu-
tion. At the beginning phase, after the excavation (e.g., 3.2 s), the displacement of the slope exhibited a nearly uniform distribution (Fig. 6(a)). The displacement contour lines were basically parallel and increased from the inner slope to the slope surface, thus demonstrating that there was no evidence of localized deformation. This can be regarded as the uniform deformation phase, according to the displacement distribution.

As can be seen from the photographs in Fig. 6, a vertical crack appeared in the slope crest as the time increased (e.g., 9.3 s); it finally extended to 5 cm in depth (Fig. 6(b)). Accordingly, a concentration of horizontal displacement contours occurred in this area. This is consistent with the common understanding that cracks are caused by tension. On the other hand, there was a concentration on the displacement contours, in horizontal direction, near the excavation surface. It can be concluded that the slope entered the phase of strain localization. In this phase, the slope exhibited a non-uniform deformation distribution with a tendency to concentrate in a narrow area. The deformation concentration developed with the increasing excavation time. A significant concentration area came into focus in the displacement field at 22.8 s, as local relative sliding occurred near the slope toe (Fig. 6(c)). This demonstrated that the slope entered a failure phase in which the local failure gradually extended to the final slip surface. The slope collapsed with a run-through slip surface at 25.6 s. After that time, the slip surface was easy to distinguish (Fig. 6(d)).

The displacement histories of four typical points along the slope were measured to illustrate the deformation phases in detail (Fig. 7). It can be seen that all the displacement history curves for the four measurement points can be regarded as straight lines during the uniform deformation phase. During the strain localization phase, the displacement histories exhibited significantly different features on different sides of the slip surface. On the inner side of the slip surface, the increase in the displacement of two points (A and B) slowed down with the increasing excavation time, while the displacement of the two points on the outer side of the slip surface (C and D) increased with a nearly invariable rate as that during the uniform deformation phase (Fig. 7(b)). This difference in displacement features became more significant when the slope entered the failure phase, namely, the displacement of the points inside the slip surface became stable with the increasing excavation time, while the displacement of the points outside the slip surface exhibited a rapid increase, demonstrating the occurrence of a landslide.

It can be seen from Fig. 6 that the maximum displacement of the slope, in both horizontal and vertical directions, occurred near the slope surface. For example, the maximum horizontal displacement increased with the increasing excavation time; however, its position exhibited little change before global failure occurred (Fig. 8(a)). Figure 8(b) shows the maximum horizontal displacements at an excavation time of 8 s, the period before the
Fig. 7. Displacement histories of typical points of excavated slope in test #1. $t$: excavation time, $u$: horizontal displacement, $v$: vertical displacement

Fig. 8. Maximum horizontal displacement of slope (at model dimensions). $t$: excavation time, $u$: horizontal displacement, $y$: vertical distance between slope toe and location of maximum horizontal displacement, $H$: slope height

Fig. 9. Displacement history (at model dimensions) of typical points of excavated slope in test #1. $t$: excavation time, $u$: horizontal displacement, $v$: vertical displacement

EXCAVATION INFLUENCE ANALYSIS

It can be seen from the contour lines of the slope that the excavation-induced deformation was restricted to a limited area (Fig. 6). A detailed examination was conducted on the influence of the excavation according to the horizontal displacement distribution. Figure 9 shows the occurrence of the landslide, in different centrifuge model tests. This provides conditions under which the displacements were comparable. The position is indicated only using the elevation, since the maximum displacement always appeared near the slope surface. It is revealed that the excavation-induced displacement of the slope can be increased through an increasing slope inclination, an increasing slope height (i.e., $g$ level) and an increasing excavation height. The position of the maximum displacement was located in the middle part of the slope, and it was significantly affected by the inclination of the slope.
horizontal displacement distribution at different elevations of 1.2:1 slope (test #1). The horizontal displacement was fairly small on the inner side, and an inflexion, at a displacement of nearly zero, occurred along the distribution curve of the horizontal displacement. On the right side of this inflexion, the horizontal displacement exhibited an obvious increase, where it can be inferred that the excavation had a significant effect. Thus, the inflexion can be recognized as a boundary point to distinguish the significant effect of the excavation on the displacement of the slope. Closer examination of the distribution curves at different elevations demonstrated that the locations of the inflexion moved to the surface with a decreasing elevation. Therefore, a surface can be accurately determined by connecting all the inflexions at different elevations, as shown in Fig. 9 using dashed lines. This surface was termed \( A\)-surface to describe the boundary of the area significantly influenced by the excavation. The \( A\)-surfaces at different times were compared (e.g., Figs. 9(a) and (b)), and the results showed that the \( A\)-surfaces were nearly invariable as the excavation time increased. This demonstrates that the area significantly influenced by the excavation was dependent only on the features of the excavation and the slope, but independent of the excavation time.

The \( A\)-surfaces were confirmed by comparative tests. Figure 10 shows the \( A\)-surfaces in the excavation model.
tests with different slope inclinations, different excavation heights and different g levels (i.e., slope heights). It can be seen that the A-surfaces were approximately parallel to the slope surfaces. A 1.2:1 slope was used to compare the effect of the excavation height on the A-surfaces (Fig. 10(a)). The results of the observation showed that larger excavation heights caused the A-surfaces to move into the slope; however, the A-surfaces exhibited similar curve patterns for different excavation heights. This can be preliminarily explained by the fact that a smaller excavation size induced fewer disturbances to the original balanced stress conditions in the slope and that smaller parts of the slope needed to deform in order to eliminate the influence of the excavation. The inclination of the slope had a significant effect on the A-surfaces (Fig. 10(b)). The A-surfaces of the 2:1 slope also looked parallel to the slope surface. The steeper slope (e.g., 2:1) had A-surfaces closer to the slope surface than the gentler slopes (e.g., 1.2:1) if an excavation height of 8 cm was maintained. This demonstrates that the excavation influenced a larger area of the slope with the decreasing inclination of the slope. The g level, indicating the slope height, also affected the position and the pattern of the A-surfaces (Fig. 10(c)), namely, a smaller slope height caused the A-surfaces to move a little into the slope. It can be inferred that the excavation-influence zone may be reduced by increasing the inclination and/or the height of the slope, perhaps because slopes are prone to failure under such conditions.

Slope failure is concluded to definitely have appeared in the excavation-influence zone. A-surfaces can be used to direct the reinforcement design of excavated slopes. For example, reinforcement structures can be arranged in the excavation-influence zone to acquire a better reinforcement effect.

### FAILURE PROCESS ANALYSIS

#### Strain Localization

A strain analysis was conducted to further understand the strain localization of slopes due to excavations. An isoparametric four-node square element, 8 mm in side length, was used. The displacement of the node was measured using an image analysis, and the strain components could be computed based on the finite element algorithm. Thus, the accuracy of the strain was estimated to be around 0.2% if using linear interpolation. In fact, the resolving capacity of the computed strain seemed to be higher in a few cases under conditions of small strain due to the use of the isoparametric element. Figure 11 shows the horizontal distribution of strain at an excavation time of 8.3 s during the strain localization phase (test #1), located near the middle of the slope where the strain was relatively large. It can be seen that the horizontal strain and the shear strain exhibited similar distributions, namely, there was a narrow zone (around X = -9 cm) with a significantly larger strain. This demonstrated that there was a significant strain localization area, which can be indicated by either the horizontal strain or the shear strain. Figure 12 shows the horizontal strain distribution of the 1.2:1 slope at different elevations and different excavation times (test #1). It is seen that the horizontal strain increased with an increasing excavation time; however, the distribution features were maintained. There were obvious areas of strain localization at all elevations.

In this paper, the strain localization area can be approximately determined using the horizontal strain distribution at different elevations. The strain localization area at an elevation is defined as the zone where horizontal strain $\varepsilon_x$ satisfies the following equation:

$$\varepsilon_x \geq k \cdot \overline{\varepsilon}_x$$ (1)

where $\overline{\varepsilon}_x$ is the average horizontal strain along a horizontal line of the slope and $k$ is the coefficient which assures that the strain localization area is relatively significant. In this paper, $k$ was set to 1.2 in all the tests, according to the test observations, for a comparison. It should be noted that $k$ is an important parameter for describing strain localization; thus, its determination needs further study. The strain localization areas at different elevations are outlined in Fig. 12. It can be seen that the horizontal strain increased, while the strain localization area was nearly invariable before the global failure of the slope with increasing excavation time. It can be concluded that the degree of strain localization increased as the time increased.

The strain localization area of the slope can be obtained according to this series of strain distributions at different elevations. Figure 13 summarizes the strain localization areas in the slopes with different inclinations. It can be seen that the inclination of the slope affected the width and the location of the strain localization area.

#### Formation Process of Slip Surfaces

The formation process of slip surfaces due to excavations was analyzed on the basis of the relative displacement histories of point couples on the slope. Each point couple was selected along the slip surface and located on
both sides at an interval of 1 cm (Fig. 14(a)). Figure 14(b) shows the histories of the relative displacements of the point couples in the 1.2:1 slope after the excavation (test #1), tangential and normal to the slip surface, respectively. It can be seen that the relative displacement increased with the increasing excavation time, and that the rate of increase became more significant from the moment at which a local slide appeared. The moments of sliding occurrence were marked using dashed lines in Fig. 14(b). It is seen that the local failure appeared progressively from the bottom to the top of the slope. In other words, the excavation-induced slip surfaces firstly occurred near the excavation surface and gradually extended upwardly to the slope surface. In addition, the normal component of the relative displacement was less than the tangential component in the lower part of the slope, indicating shear failure. In the upper part, however, the normal component was larger than the tangential component, indicating the dominant role of tension failure.

Figure 15 shows the slip surfaces and the formation process of the slopes with different inclinations. The upper part of slip surfaces exhibited a tendency to move into the slope with an increasing slope inclination. The inclination also had an effect on the formation process of the slip surfaces. For example, the moments of the occurrence of slip surfaces were significantly different for different inclinations. This implies that failure mechanisms are different for slopes with different inclinations, and further study is required on the basis of systematic tests. The data analysis, on the other hand, revealed that all the formation processes for slip surfaces are similar, namely, the slide firstly occurs near the excavation surface and then extends upwardly to the slope surface under excavation conditions. This demonstrates that excavations induce similar failure processes for slopes.

The strain localization areas and the final slip surfaces are compared in Fig. 16. It can be seen that the lower part of the final slip surface was located in the strain localiza-
tion area; however, the upper part of the final slip surface was out of the strain localization area. This demonstrates that the strain localization area in the lower part of the slope finally developed into the slip surface with shear failure. The upper part of the slip surface was formed mainly by the tension of the sliding soil mass, which was mostly dependent on the slope inclination and the direction of the crack propagation. This can partly explain why slope inclination significantly affects the occurrence times of slip surfaces.

**CONCLUSIONS**

An in-flight excavation device was realized based on the centrifuge at Tsinghua University to simulate a live excavation of a slope at high g levels in centrifuge model tests. A series of centrifuge model tests was conducted to simulate a single excavation of an unsaturated silty clay slope with different inclinations and heights, and the excavation height was also involved. The displacement histories of points over the slope were measured by the image-capture and displacement-measurement system and used to analyze the deformation and the failure behavior of slopes under excavation conditions. The following con-
CENTRIFUGE MODELING OF EXCAVATED SLOPES

Fig. 15. Final slip surface in slopes with different inclinations. \( t \): excavation time, \( h \): excavation height

Fig. 16. Comparison of strain localization area and slip surface in slopes. \( t \): excavation time, \( h \): excavation height

Conclusions are drawn:

1. The excavation-induced deformation process can be divided into several phases with different features of displacement distribution, including the uniform deformation phase, the strain localization phase and the failure phase.

2. The excavation only affects a limited zone of the slope whose boundary can be outlined by the \( A \)-surface. The excavation-influenced area of the slope is dependent on the features of the excavation and the soil properties but is independent of the excavation time.

3. The excavation-induced strain localization area of the slope can be determined using strain distributions at different elevations. The degree of strain localization increases as the excavation time increases, while the width of the strain localization area is nearly invariable.

4. Shear failure firstly occurs near the excavation surface and then extends upwardly to the slope surface under excavation conditions, while tension failure plays a dominant role in the upper part of the slip surfaces.

5. The strain localization area moves to the slope surface with an increasing slope inclination, and the lower part of the final slip surface is located in the strain localization area.

It should be noted that the mechanical properties of soil have a significant effect on the response of the slope due to the excavation. The conclusions in this paper can be applied only to similar soil slopes. Further systematical tests are required for a detailed discussion on the effect of soil properties.
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