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FULL-SCALE MODEL TEST FOR PREDICTING COLLAPSE USING INVERSE OF VELOCITY OF SLOPE SURFACE DURING EXCAVATION

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Predicting the onset of slope failure or rock falls is important for occupational safety because they kill approximately ten to 20 workers every year in Japan. Approximately half of such victims are from slope failure during slope excavation and construction. In order to predict the time of slope failure during an excavation, a full-scale model slope was built, and the displacement of the slope surface was monitored during slope excavation. The surface displacement rapidly increased with the elapsed time after the excavation, and the relationship between the displacement and elapsed time included an exponential function just before collapse. Based on the results, by computing the inverse of the velocity of the slope surface displacement obtained in ten-second intervals, a warning signal can be provided five min before collapse.

Keywords: Slope failure, Slope-cutting work, Warning signal, Occupational accident, Model test, Displacement sensor.

1 INTRODUCTION

Occupational accidents due to soil movement are decreasing, but approximately 20 people are still sacrificed every year in Japan. Figure 1 shows the number of fatalities resulting from occupational accidents caused by slope excavation, trench excavation, and others from 1985 to 2015 in Japan based on data from the construction industrial labor accident reports of the Japan Construction Safety and Health Association (JCSHA). Occupational accidents due to soil movement can be broadly divided into those from slope excavation and trench excavation.

In many cases, slope failure is likely to occur rapidly, which leaves most construction workers with insufficient time to escape from excavation sites. Slope excavation needs hard or soft prevention measures during excavation. These prevention measures include a temporary retaining wall, the installation of a proprietary shorting system, and a monitoring system for slope deformation that can issue an alert.

In this study, we focused on slope deformation in order to predict the onset of slope failure or rock falls to improve occupational safety during slope excavation and help establish a monitoring system that provides an alert. In order to confirm the behavior of a slope during excavation and verify the predicted time of slope failure, a full-scale model slope was excavated, and the displacement of the slope surface was monitored.

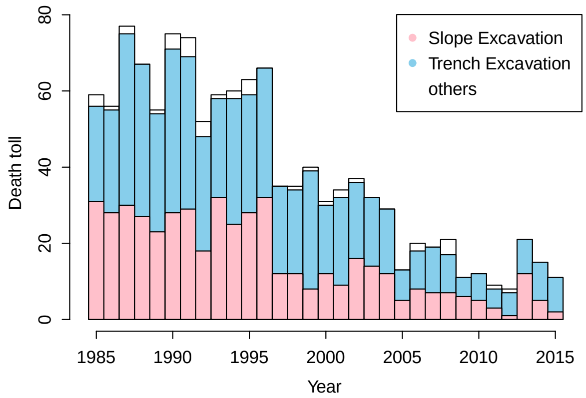


Figure 1. Number of deaths from occupational accidents.

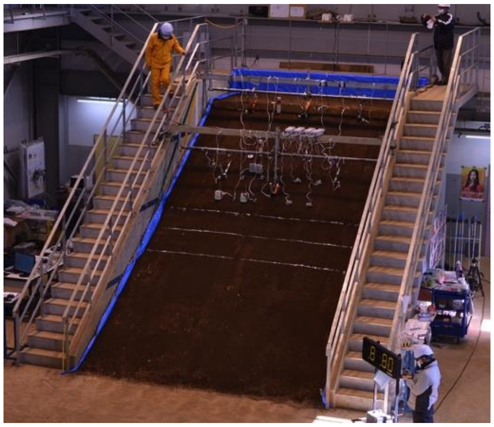


Figure 2. Full-scale slope model.

2 EXPERIMENTAL SETUP

An excavation was carried out in a full-scale model test to predict the collapse. Figure 2 shows the initial dimensions of the slope: 30° angle, four meter width, and 3.5 meter height. The soil was Kanto loam, which is a commonly deposited volcanic cohesive soil present in Tokyo. The initial water content of the soil was set to around 90%, and the soil was filled to a wet density of around 1.00 g/cm^3 for each layer, which had a height of 0.5 m. The water content and wet density were obtained through a water content test and density test using an RI densimeter on each layer. In the test results, the initial mean water content was 88%, and the mean wet density was 0.98 g/cm^3. Figure 3 shows the monitoring equipment used: four strain gages underground, 12 clinometers, two extensometers, and 12 displacement sensors. The displacement sensors that were set parallel and vertical to the slope at six points measured the movement of the target set on the slope, as shown in Figure 4.

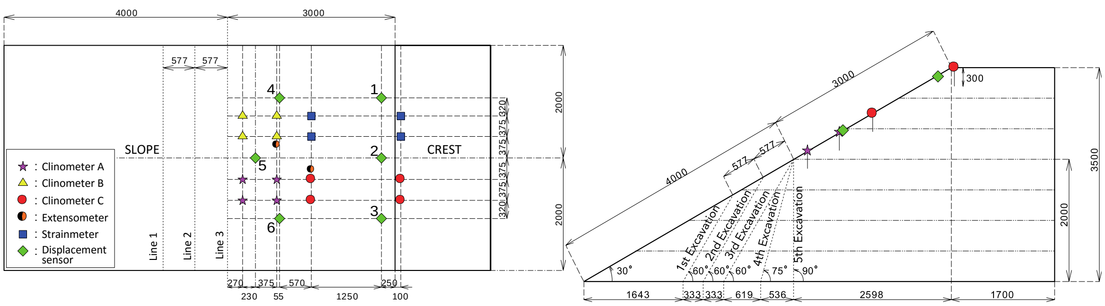


Figure 3. Projection and cross-sectional views of the experimental setup.

3 EXPERIMENTAL RESULTS

For slope cutting, the slope was excavated at 60° at various heights with a drag-shovel in the first to third stages and cut at 75° and 90° at two meters from the bottom in the fourth and fifth stages, respectively. Because the bucket was 1.8 m in width, the drag shovel excavated three times in the order of center, left, and right along a single line in each excavation stage. The time interval between each excavation stage was a minimum of 30 min; it was 60 min between the third and fourth excavations and 90 min between the fourth and fifth excavation because of the slope moving according to the monitoring data. A small area of the slope collapsed in the fifth stage. Thereafter, the colluvial soil was removed in three more stages (sixth to eighth stages); the whole slope failed after the eighth stage. Figure 5 shows each cutting cross-sectional surface at the center obtained by the 3D laser survey.

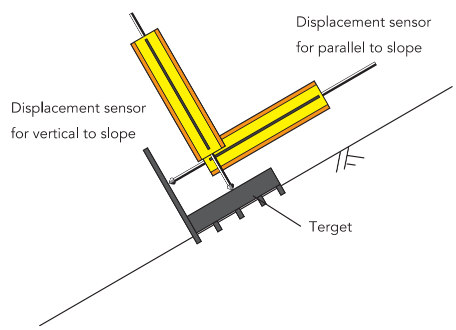


Figure 4. Displacement sensor setting.

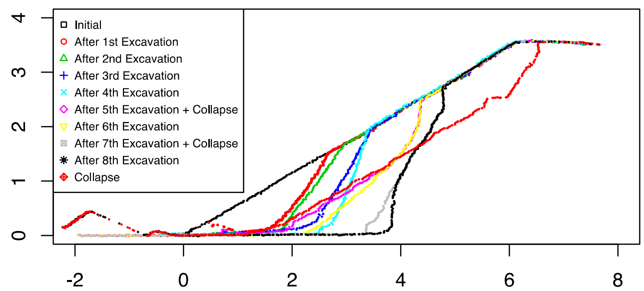


Figure 5. Cross-sectional surface at the center of each stage.

We focused on the data of the displacement sensors on the slope surface. Figure 6 shows the change in displacement parallel to the slope. The data obtained by displacement sensors four to six that were set on the lower part of the slope showed large displacement during the excavation that later converged in the first to fourth excavation stages. Then, the displacement increased with each excavation stage. Therefore, the slope became more dangerous with each step. On the other hand, the data from displacement sensors one to three that were set on the upper part of the slope remained mostly unchanged during the first to seventh excavations.

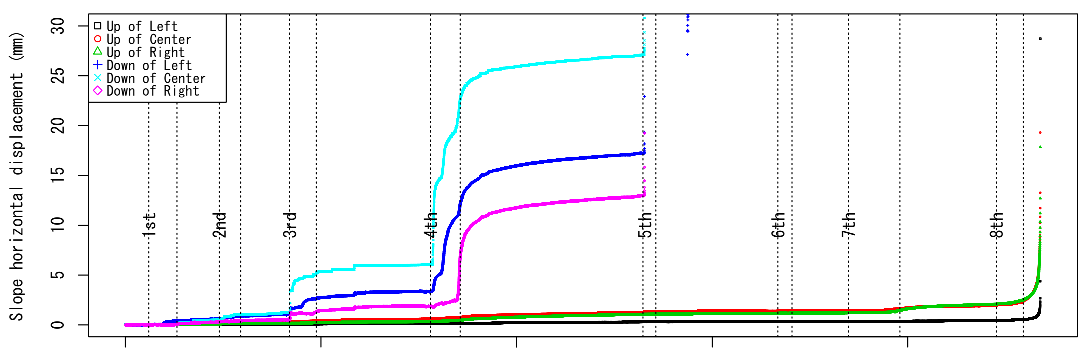


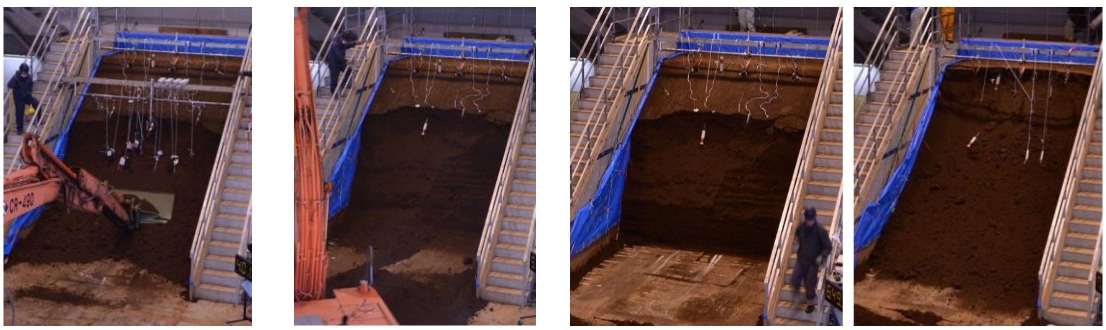
Figure 6. Displacement parallel to the slope surface.

A small collapse occurred during the fifth excavation stage, as shown in Figure 7, and displacement sensors four to six could not take measurements after that. We decided to continue excavating the slope as well as perform restoration work in order to remove the colluvial soil generated by the small collapse in the sixth to eighth excavation stages. In the sixth excavation stage, the colluvial soil that stood at 30° was cut to 40° at a starting point 1 m from the bottom. The seventh excavation was cut at a 60° angle with the top of the collapse that occurred in the fifth excavation stage as a starting point, and a small collapse occurred on the left part of the slope. Displacement sensors one to three could not detect anything at these excavation points before the small collapse compared to sensors four to six. Finally, the slope was excavated to 90° in the eighth excavation with the starting point at one meter from the bottom of the slope.

Deformation could not be found by a visual check soon after the eighth excavation, but the data showed an increase in the displacement obtained by sensors one to three regarding creep deformation. The displacement continued increasing, and a large collapse occurred seven minutes after the eighth excavation, as shown in Figure 7. The surface displacement rapidly increased with the elapsed time, and the relationship between the displacement and elapsed time included an exponential function just before the collapse.

Based on the experimental results, slope collapse was classified into two types: collapses that occur during and after excavation. The latter has a higher risk than the former because workers stay off the slope during excavation but approach the slope after excavation. It is more important to evaluate whether a slope is stable or not after excavation.

In the next section, we discuss the possibility of predicting slope failure by means of slope surface displacement.



Collapse during fifth excavation | Collapse during seventh excavation | Just after eighth excavation | Collapse after eighth excavation

Figure 7. Collapse of the slope model in each part.

4 WARNING SIGNAL FOR COLLAPSES

Fukuzono (1985) proposed equations to predict the time of collapse. We applied a method of using the inverse of the velocity of the displacement of the slope surface as proposed by Fukuzono's equations. It is important for workers to escape based on judgment of the danger at that time, rather than the predicted time of collapse. The inverse of the velocity was used to check the emergency safety. The velocity increases to infinity at collapse, so the inverse of the velocity effectively approaches zero.

Tamate *et al*. (2013) proposed a signal for an emergency safety method that uses the inverse of the velocity of the slope strain. There are two types of signals: the first signal judgment is based on a threshold value for the inverse of the velocity of the strain, and second signal judgment is based on whether or not the inverse of the velocity of the strain shows an accelerating change.

We applied the same method as Tamate *et al*. (2013); however, we used the displacement instead of the strain. We propose a warning signal that uses a predicted line based on the inverse of the velocity at each interval; the signal is triggered when consecutive plots fall below the predicted line, as shown in Figure 8. Therefore, the warning signal provides a qualitative evaluation. The judgment of the warning signal can be based on some method. For example, three parameters were validated for computing the velocity, choosing the points for the predicted line, and determining how often the plot falls below the predicted line. The number of points to compute the predicted line was fixed to two points in order to reduce the calculation cost. The number of points that fall below the predicted line before a warning signal is given was fixed to two points. Increasing the number of points would improve the prediction accuracy but delay the warning timing.

The velocity of an arbitrary time is computed from the previous and following displacement. The displacement sensors obtained data at one-second intervals; thus, the minimum time for computing the velocity was two seconds. The plots of the inverse of the velocity were extracted as positive values, and the predicted lines were extracted as negative values to protect against false signals.

Four cases with different times for the computed velocity and/or plots used for the predicted line were conducted, as presented in Table 1.

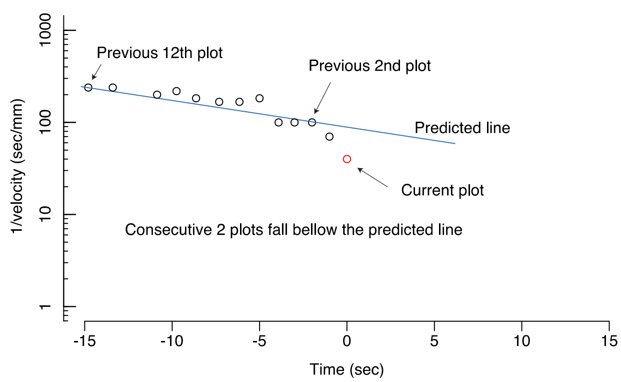


Figure 8. Judgment method for the warning signal in cases 1 and 2.

Table 1. Setup and results of each case.

	Data interval	Time for computing velocity	Plots for computing the predicted line	Signal time between first warning and collapse
Case 1	1 s	± 1 s	Previous second and tenth plots	45 s
Case 2	1 s	± 10 s	Previous second and tenth plots	18 min 27 s
Case 3	10 s	± 10 s	Previous second and third plots	1 min 7 s
Case 4	10 s	± 10 s	Previous second and fifth plots	5 min 7 s

The warning signals were calculated by using sensor two, which was set at the center of the upper part. For each case, the last collapse was evaluated. Figure 9 shows the results of the judgment of warning signals after the eighth excavation in each case. The last column of Table 1 presents the first warning signal time before collapse.

The warning signal was issued 18 min 27 s before collapse in case two. The parameters of case two provided better results than the other cases; however, the displacement sensor required higher power consumption because data were provided in one-second intervals. The parameters of case four were assumed to be a good example of actual operations in the field.

5 CONCLUSION

In order to confirm the behavior of a slope during excavation and verify the prediction of slope failure, an experimental test was conducted on a full-scale model slope, and the displacement of the slope surface was monitored during slope excavation. We validated a method of using the inverse of the velocity of the slope displacement to provide a warning signal. The results showed that the warning signal could be provided 18 min before collapse by monitoring data at one-second intervals and five minutes before collapse at ten second intervals.

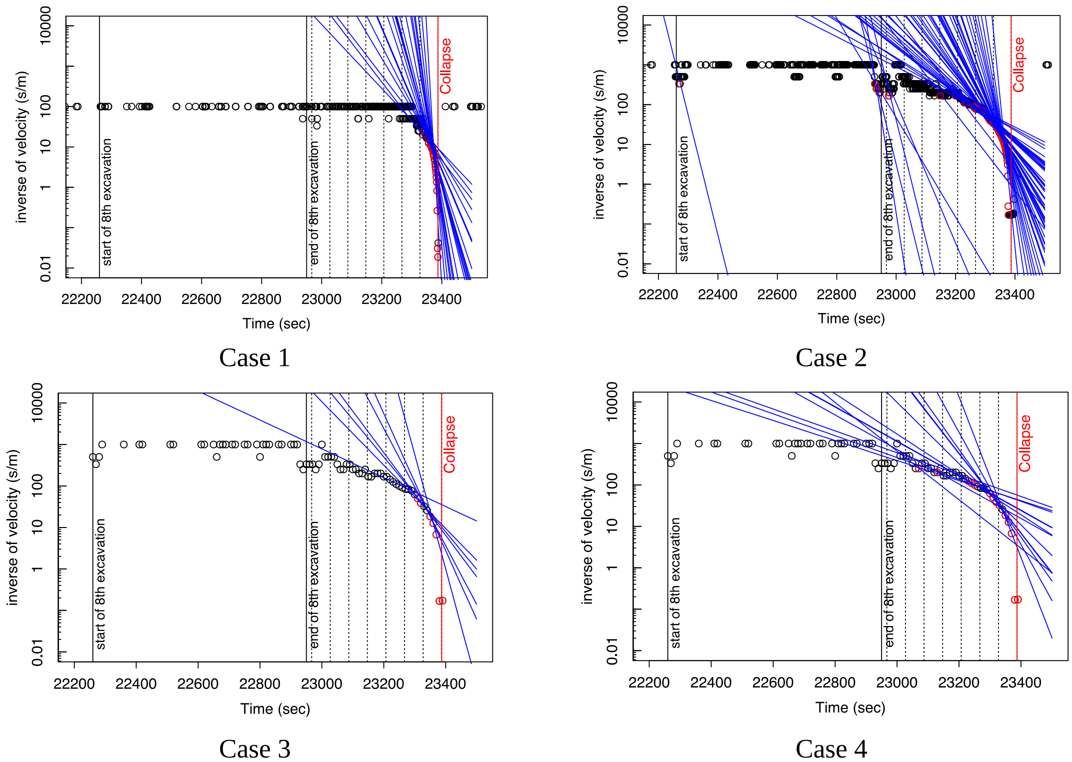


Figure 9. Warning signals after the eighth excavation calculated by using sensor 2.

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