Maximum width of undercut slope with planes of discontinuity studied by 1G physical models

T. Techawongsakorn and T. Pipatpongsai
i) Ph.D Student, Department of Civil and Environmental Engineering, Tokyo Institute of Technology, 2-12-1, Ookayama, Meguro, Tokyo 152-8552, Japan.
ii) Assoc. Prof., Department of Civil and Earth Resources Engineering, Kyoto University, C1-4-292, Nishikyo-ku, Kyoto 615-8540, Japan.

ABSTRACT

Physical models of undercut slope have been successively studied in order to cope with the mining problem at the Mae Moh open-pit coal mine in Lampang province of Thailand, where the layers of coal working as counterweight along to toe of the slope are excavated without prior removal of unstable rock masses. Previous research has convinced the mechanical idealization by validating with the results of physical models with sufficient reliability for practical designs. However, the effects of faults existing at the actual site have not included in the previous study. Therefore, undercut slope models were improved by inserting faults to the physical model in the present study. This paper focuses on the maximum undercut width of physical models in regard to both symmetrical and unsymmetrical discontinuous planes. Experimental procedures and controlled conditions were clarified including water content and bulk density as well as construction sequences of the modeled slope. The results observed from the experiments were compared with the theoretical idealizations based on the beam failure assumptions and the existing arch failure assumptions which are strip arch with soil slip, segmented arch with stable scarp, and circular arch with upheaval buckling. Formulation of the derived equations for predicting the maximum width were explained and discussed with an aim to identify the factors causing agreement and disagreement with the experimental results.

Keywords: undercut slope, discontinuous planes, slope stability, physical model, failure mechanisms

1 INTRODUCTION

Physical model of undercut slope has been continually studied in order to cope with a problem of mining at Mae Moh, open-pit coal mine in Lampang province, Thailand, where layers of coal working as counterweight along to toe of the slope are excavated without prior removal of unstable rock masses. A certain relative displacement is permitted to initiate arch action across the excavated pit; therefore, sliding force of slope can be transferred laterally without causing failure of slope.

Former research has shown a good agreement between the idealization and the result of physical modelling so that it can be applied to the actual site. However, there are some areas that have faults which affect to the stability of the slope. So undercut slope technique is needed to be developed by inserting the fault to the physical model. The result and discussion about the physical modelling of undercut slope with symmetrical and unsymmetrical discontinuous planes will be shown. This paper focuses on the maximum width of physical model comparing to the theoretical.

2 OVERVIEW OF THE EXPERIMENT

For this set of experiments, silica sand no.6 is used to model the slope with basal support. First of all, six samples are collected into the small plate, 3 from the top and another 3 from the bottom of tank. All of them have been weighted before dried in the oven for 30 minutes. Secondly, the water content percentage can be calculated by weighting dried samples. Due to evaporation, the water is always added in order to maintain 10% of moisture content. Next the basal support with the dimension 1.30 m width, 0.40 m length and 0.06 m thickness is made of silica sand on the acrylic plate with controlled bulk density at 13.68 kN/m$^3$. To control bulk density, the first row with dimension 1.30 m width, 0.05 m length and 0.06 m thickness is compacted and the side surface is scratched for not making discontinuous plane. Then the second row with another 0.05 m length is added next to the first one. This process is repeatedly done until reaching 0.40 m length. Then the slope part with dimension 1.30 m width, 0.80 m length, 0.06 m thickness and inclined angle 40° is also made of silica sand on the Teflon sheet with the same controlled bulk density at 13.68 kN/m$^3$. Silica sand is filled and compacted on top.
every 0.05 m and scratched on the top surface for making continuous interface planes until reaching 0.80 m length. After that, three faults are inserted into slope part. There are two series which are conducted. The first one is three parallel faults at 0.15 m, 0.25 m and 0.35 m of slope part from the bottom as shown in figure 1. For this series, there are three experiments with different dip direction i.e. faults in vertical direction, normal to slope part and horizontal direction as shown in figure 2. The second one is three alignments of fault from bottom-left corner of slope to top-middle, top-right corner and middle-right as shown in figure 3. For this series, there are also three experiments with the same dip direction as the previous series. Finally, High speed camera and digital camera are set up in front of slope to capture video and photos which is used for observing failure mechanisms and Particle Image Velocimetry (PIV) analysis respectively.

After preparation has been done, basal support part is excavated every 5 cm width from center line. Next digital camera captures a photo for PIV analysis. Then the pit width is expanded until the first failure is observed. While the first failure is occurring, high speed camera records video at the rate 1000 frames per second. Failure width, right and left angle of failure arch are also recorded. After recording has been done, same process is recurrently done with the second, third, fourth to the last failure which is total failure.

Fig. 1. The first series of undercut slope physical model.

Fig. 2. Different dip direction of faults.

3 THEORETICAL BACKGROUND

There are 2 assumptions of failure mechanism i.e. arching assumption and beam failure assumption.

3.1 Arching assumption

According to Pipatpongsa et al, there are 3 types of arching failure. And failure width, $B_f$, can be calculated via equation (1)

$$B_f = \frac{k \left( \sin(\alpha - \phi_i) - c_i \right)}{\gamma}$$

Where $k$ is arching coefficient i.e. $k=\cos\phi$ for strip arch with soil slip ($\phi$ is the friction angle of sand), $k=1$ for segmented arch with stable scarp and $k=4/\pi$ for circular arch with slope buckling.

Parameter $\alpha, \phi_i, c_i, \gamma$, $T$ and $\sigma_c$ are inclined angle of slope, interface friction angle between sand and bedding plane (in this experiment between silica sand no.6 and Teflon sheet), interface adhesion between sand and bedding plane, unit weight, thickness of slope and unconfined compressive strength.

3.2 Beam failure assumption

From figure 4, plastic moment, $M_p$, can be determined via equation (2).

$$M_p = \frac{h}{2} = \frac{1}{2} bh^2 \frac{a}{1 + a} \sigma_c$$

Where $\sigma_c = \frac{1-\sin\phi}{1+\sin\phi} \sigma_c$ is uniaxial tensile strength, and $a = \frac{1-\sin\phi}{1+\sin\phi}$
From figure 5, collapse load, \( w \), can be derived via following equation:

\[
M_p \theta + 2M_p \theta = 2 \int_0^t w x \theta dx
\]

\[
4M_p \theta = \frac{wdt^2}{4}
\]

\[
w = \frac{16M_p}{l^2}
\]

Let \( t = B_f \);

\[
B_f = 4 \sqrt{\frac{M_p}{w}}
\]

From figure 6, uniformly distributed load by using equilibrium of soil mass sliding along the bedding plane can be determined via equation (5);

\[
w = \gamma ts \left( \sin \alpha - \tan \phi_i \cos \alpha - \frac{c_i}{\gamma T} \right)
\]

So the failure width, \( B_f \), of beam failure assumption can be determined by using equation (2), (4) and (5).

### 4 MATERIAL PARAMETERS

| Water content of moist silica sand no.6 | 10% |
| Bulk unit weight of moist silica sand no.6 ( \( \rho = 1395 \text{ kg/m}^3 \)) | \( \gamma \) (13.68 kN/m³) |
| Unconfined compressive strength of moist silica sand no.6 | \( \sigma_c \) (1.59 kPa) |
| Interface adhesion between Teflon plate and moist silica sand no.6 | \( c_i \) (0.15 kPa) |
| Interface friction angle between Teflon plate and moist silica sand no.6 | \( \phi_i \) (21.0°) |
| Thickness of slope made of moist silica sand no.6 | \( T \) (0.06 m) |
| Friction angle of silica sand no.6 | \( \phi \) (41.5°) |

As has already been discussed above, water content has been measured and readjusted before experiments are conducted. Bulk unit weight is controlled during slope preparation. For unconfined compressive strength of moist silica sand no.6, it is obtained from triaxial test. Friction angle of moist silica sand no.6 is obtained from simple direct shear test. Lastly, interface adhesion and interface friction angle between Teflon plate and moist silica sand no.6 are also obtained from simple direct shear test.

### 5 EXPERIMENTAL RESULTS

| Series | 1 | 2 | 3 | 4 | 5 | 6 |
|--------|---|---|---|---|---|---|
| Test No. | 1 | 2 | 3 | 4 | 5 | 6 |
| \( B_f \) (cm) | 32.5 | 42.5 | 60 | 35 | 47.5 | 55 |

Table 2 shows results of the first series which faults are three parallel lines. For test no.1, faults are drawn in vertical direction. Failure is observed at 32.5 cm width. For test no.2, faults are drawn perpendicular to slope plane. Failure is observed at 42.5 cm width. And for test no.3, faults are drawn in horizontal direction. Failure is observed at 60 cm width.

The second series is the slope with three faults which are arranged as stated. For test no.4, faults are drawn in vertical direction. Failure is observed at 35 cm width. For test no.5, faults are drawn perpendicular to slope plane. Failure is observed at 47.5 cm width. And for test no.6, faults are drawn in horizontal direction. Failure is observed at 55 cm width.

Figure 7 shows relationship between the result of experiment and linear equation from idealization. All of six points are the result from all six tests. Graph plotted between \( X = \sigma_c / (\gamma B_f) \) and \( Y = (\sin(\alpha - \phi_i) / \cos \phi_i) - (c_i / (\gamma T)) \). There are also three different linear lines corresponding to different arching coefficients, of arching assumption. Blue, brown and black line correspond to \( k = \cos \phi_i \), 1 and \( 4/\pi \) respectively.

The result shows that only test no.3 and 6 show a good agreement i.e. failure widths of test no.3 and 6 are more than failure width from the assumption. For test no.1, 2, 4, and 5, failure widths are less than the assumption. So there is no arching effect to test no. 1, 2, 4, and 5.
As can be seen in figure 8, failure mode of test no.2 is similar to beam failure and the cross section shape is rectangular with dimension 6 cm x 15 cm. So test no.2 is chosen to compare the result with idealization. From equation (2), (4), and (5), failure width, $B_f = 37.7$ cm while the failure width from the experiment, $B_f = 42.5$ cm.

6 DISCUSSIONS

Using arching assumption does not show a good agreement with the results from experiment except by test no.3 and 6. By using $k=\cos\phi$, failure width from arching assumption equals 52.4 cm which is less than failure width of test no.3 (60 cm), and test no.6 (55 cm). Because failure mode is the arching failure (see figure 9 and 10).

For test no. 2, failure modes are similar to beam failure and the result of the experiment shows a good agreement with idealization.

7 CONCLUSIONS

Different dip direction of faults causes the different failure width and failure mechanism. Tests which dip directions of faults are in vertical direction and perpendicular to the slope plane result narrower failure width and beam failure mechanism. And tests which dip direction of faults is in horizontal direction result wider failure width and arch failure mechanism.

8 ACKNOWLEDGEMENT

This research work was funded by the Electricity Generating Authority of Thailand (EGAT) under the research project grant “Failure mechanisms and stabilization of undercut slope with faults at Lowwall Area 4.1 by using shear pins and rock bunds”.

REFERENCES

1) Pipatponsa, T., Khosravi, M.H., Stathas, D., Leelasukseree, C. and Takemura, J. (2012): Cohesive Arch Action in Laterally Confined Block of Moist Sand Placing on an Inclined Bedding Plane, 7th Asian Rock Mechanics Symposium.
2) Khosravi, M.H., Tang, L., Pipatponsa, T., Takemura, J. and Doncommul, P. (2012): Performance of counterweight balance on stability of undercut slope evaluated by physical modeling, International Journal of Geotechnical Engineering.
3) Pipatponsa, T., Khosravi, M.H. and Takemura, J. (2013): Physical modeling of arch action in undercut slopes with actual engineering practice to Mae Moh open-pit mine of Thailand, The 18th International Conference on Soil Mechanics and Geotechnical Engineering.
4) Khosravi, M.H., Pipatponsa, T. and Takahashi A. (2011): Arch Action over an Excavated Pit on a Stable Scarp Investigated by Physical Model Tests, Soils and Foundations.
5) Techawongsakorn, T., Hirai, H., Khosravi, M.H. and Pipatponsa, T. (2013): Slip mechanisms and interface shear strength between moist silica sand and acrylic plate, The 48th Japan National Conference on Geotechnical Engineering.
6) Khosravi, M.H., Pipatponsa, T. and Takemura, J. (2012): Arching effect in geomaterials with applications to retaining walls and undercut slopes, Department of International Development Engineering, Graduate School of Science and Engineering, Tokyo Institute of Technology.
7) Hirai, H. and Pipatponsa, T. (2013): Geometrical Shape of Arch Formed by Collapse of Undercut Slope, Department of International Development Engineering, Tokyo Institute of Technology.