Physical modeling of arch action in undercut slopes with actual engineering practice to Mae Moh open-pit mine of Thailand

Modélisation physique de l'effet de voûte dans les pentes en déblai en suivant la pratique de l'ingénieur pour la mine à ciel ouvert à Mae Moh en Thaïlande

Pipatpongsa T.
Global Scientific Information and Computing Center, Tokyo Institute of Technology

Khosravi M.H., Takemura J.
Department of Civil and Environmental Engineering, Tokyo Institute of Technology

ABSTRACT: In the field of mining engineering, a stable arch formed across a pit is beneficial to the design of an undercut slope; therefore, prediction of the maximum stable undercut width under which the slope does not collapse is needed. The relation between a stable width and an inclined angle has been obtained experimentally to confirm the developed theoretical relations. A series of simple experiments using a block of compacted moist sand confined by parallel rigid walls has been conducted by varying the thickness, width and length. The actual engineering application was immediately tested at the Mae Moh open-pit mine in Thailand. The factor of safety in fully saturated condition with hydro-static water pressure on bedding shear was evaluated. It is concluded that this novel procedure in mining is practically realizable and results in reductions in massive excavation, transportation and dumping of unstable rock mass, as well as saving an amount of time and expense.

RÉSUMÉ : En génie minier, la formation d'une voûte stable au-dessus de l'excavation fournit un avantage pour la conception d'une pente en déblai; par conséquent, la prédiction de la largeur du déblai maximale, qui ne provoque pas d'effondrement, est nécessaire. La relation entre une largeur stable et un angle d'inclinaison a été obtenue expérimentalement pour confirmer les relations théoriques. Une série d'expériences simples utilisant un bloc de sable humide compacté confiné par des mur rigides parallèles a été menée en variant l'épaisseur, la largeur et la longueur. La pratique de l'ingénieur est immédiatement appliquée pour la mine à ciel ouvert à Mae Moh en Thaïlande. Le coefficient de sécurité dans un état complètement saturé avec la pression hydrostatique sur la zone de cisaillement a été évalué. Il est conclu que cette nouvelle procédure de l'exploitation minière est réalisable, entraînant une réduction du volume d'excavation, du transport et du déversement de la masse rocheuse instable, ainsi qu'une économie de temps et d'argent.

KEYWORDS: arching effect, undercut slope, excavation, physical model, open-pit mining.

1 INTRODUCTION

Evaluating the stability of slopes is one of the most important activities in geotechnical engineering. The existence of a stable scarp in some slope failures along oblique faults can be evidence of an arching effect in those slopes. Pipatpongsa et al. (2009) reported the existence of some stable scarps in huge slope failures in the Mae Moh coal mine. Exposed scarps of a slope failure remains stable if the material has a sufficient strength to resist the load transferred to the stable adjoining parts. This phenomenon of load transfer from the yielding part of the material to the adjacent stationary parts is known as the arching effect (Janssen 1895 and Terzaghi 1936).

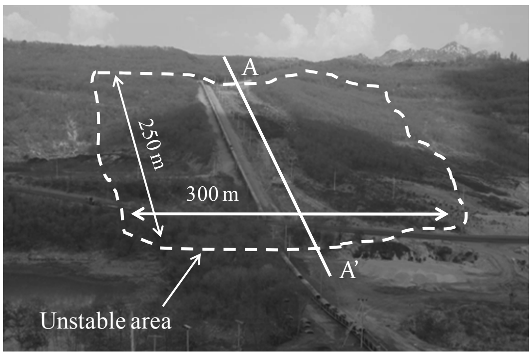

Figure 1. Unstable Area 4.1 (as of September 2010)

The relation between a stable width and an inclined angle has been obtained experimentally to confirm the developed theoretical relations (Khosravi 2012) for (a) a strip arch with slip failure in laterally supported sand blocks, (b) a segmented arch with arch-shaped failure in mild undercut slopes and (c) a circular arch with buckling failure in steep undercut slopes. For the design purpose of undercut mining, this particular relation provides the maximum span of the undercut where load could laterally be transferred to vertical planes of a neighboring rock mass. A case study of an undercut slope at the Mae Moh open-pit mine in Thailand is presented.

2 SITE DESCRIPTION

The actual engineering application of the developed theory was immediately tested at the Mae Moh open-pit mine in Thailand. The Mae Moh open-pit lignite mine primarily supplies coal to generate electrical power in Thailand. The mine, under the operation of the Electricity Generating Authority of Thailand (EGAT) since 1952, is located approximately 630 km north of Bangkok in Lampang province. Currently, the annual production of the mine is about 16−17 million tons/year with a volume of excavated overburden of around 60−80 million m^3/year. Its pit has a maximum width of about 4 km and a maximum length of about 9.5 km. Green clay in the bedding shear zone has caused problems of various scales. Slopes in the Mae Moh mine are prone to plane failure once they dip out of the slope face and strike parallel to the bedding shears.

According to the full core drilling, which consists of up to 900 holes have been drilled in the Mae Moh mine during the period 1987–2005. The thickness of the bedding shear zone ranges from 10 to 80 mm. About 40% of the bedding shear zone comprises continuous layers of clay seam. In this study, the targeted area is Area 4.1, shown in Fig.1. Its cross-section is shown in Fig.2.

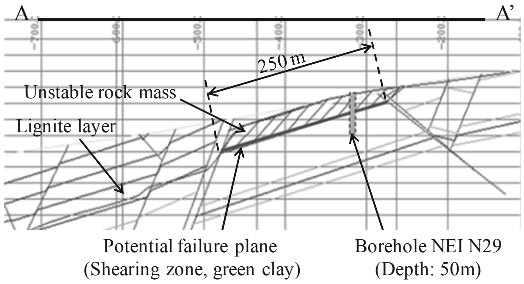

Figure 2. Cross-section A-A' of Area 4.1 (Courtesy of EGAT)

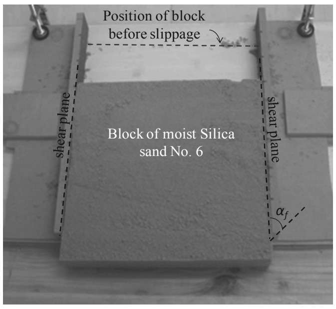

Figure 3. Slippage of the sand block along the lateral supports (after Khosravi et al. 2012)

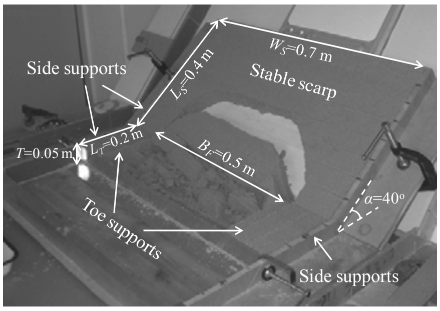

Figure 4 Arch-shaped failure in mild undercut slopes at the maximum undercut span (after Khosravi et al. 2012)

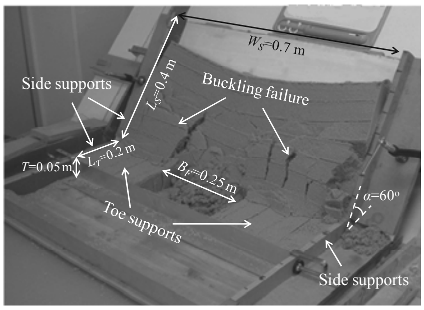

Figure 5. Buckling failure in steep undercut slopes at the maximum undercut span (after Khosravi et al. 2012)

3 PHYSICAL MODEL

Khosravi et al. (2009, 2010, 2011) have conducted a series of simple experiments using a block of compacted moist sand confined by parallel rigid walls by varying thickness, width and length. The inclined angle of the bedding plane was gradually increased until the block started to slip (see Fig.3). Also, some laboratory-scale undercut slope physical model tests were conducted under both 1G and centrifugal acceleration fields. The existence of passive arching effects in the slope models can be confirmed by means of earth pressure recordings and image processing techniques. In the undercut slopes, some parts of the load are transferred from the yielding portion of the slopes to the stiffer sides. The level of load transfer depends on the stiffness and strength of the lateral supports. Two types of slope failures can be expected: an arch-shaped failure (see Fig.4) in the central part of the slope for the strong sides, and side buckling (see Fig.5) leading to total failure of the slopes for the weak sides. In addition, the performance of a counterweight balance, which is considered a technique to stabilize undercut slopes with weak sides, was demonstrated through a series of physical models and confirmed that a wider undercut span in front of the slope can be realized (Khosravi et al. 2012).

4 THEORETICAL BACKGROUND

In chemical engineering, a stable arch formed across the orifice of a hopper causes difficulty in discharging of cohesive material; therefore, determination of the minimum diameter which destabilizes the arch action is required. On the other hand, in mining engineering, a stable arch formed across a pit is beneficial to the design of an undercut slope; therefore, prediction of the maximum undercut width which does not cause it to collapse is needed. Jenike's (1961) model for arch formation has laid the foundation for understanding the behavior of a static system of cohesive materials confined by hopper walls (Walker 1966 and Walters 1973). This study extends a basic idealization of a stationary system used by Jenike (1961) to the stability of a laterally confined rigid block inclining on a stiff bedding plane. The following similar assumptions were adopted in the present study with an additional consideration of interface resistance: (a) the resistance supporting the arch is characterized by unconfined compressive strength, and (b) the load breaking the arch is due to its own weight and to the force exerted by the material above the arch. The mechanism involved and its implication on instability can be explained in that if the load induced by weight of the arch is greater than the unconfined compressive strength and the interface resistance, the arch will collapse and therefore the widest possible span or the failure width of block B_f of a stable arch can be predicted.

The authors (Khosravi 2012) have recently developed equations to describe the instability phenomena of undercut slopes based on Jenike's (1961) theory of cohesive arching in hoppers, as shown in Eq.(1) which can be alternatively expressed by Eq.(2) in terms of the inclined angle at failure α_f for a given span of undercut B.

$$B_f = \frac{k}{\left(\sin\alpha - \tan\phi_i \cos\alpha\right) - \left(c_i/\gamma T\right)} \frac{\sigma_c}{\gamma} \tag{1}$$

$$\alpha_f = \phi_i + \sin^{-1}\left(\left(\frac{c_i}{\gamma T} + k\frac{\sigma_c}{\gamma B}\right)\cos\phi_i\right) \tag{2}$$

where α: inclined angle, T: thickness of block, ϕ_i: interface friction angle, c_i: interface adhesion, σ_c: unconfined compressive strength, γ: bulk unit weight, ϕ: friction angle of material, k: arching coefficients:

- k=0 no arching
- $k_1=\cos\phi$ strip arch with soil slip
- k_2=1 segmented arch with stable scarp
- $k_3=4/\pi$ circular arch with slope buckling

The arching effect is the ability of soil to transfer load laterally to a more rigid lateral/basal base by trajectories of the major principal stress. Failure happened along the shear plane generated by relative displacement. Because the undercut of a steep slope generates more stress relief, the shear zone is bigger with a wider shape at the top. While the shear zone of a mild slope is smaller with a wider shape at the bottom. This difference causes many failures of arches. Subsequent stacks of arches can form in a mild slope until reaching the collapse of a whole slope, while failure will happen aggressively for a steep slope due to slope buckling without many local failures.

Characterization of each type of failure is different by means of arching coefficients, k, based on theoretical mechanics and validated by the results of the physical model test. Three values of the coefficient are provided for (1) a strip arch with soil slip, (2) a segmented arch with stable scarp and (3) a circular arch with slope buckling. For a slope with no arching, the arching coefficient is merely zero.

5 APPLICATIONS TO SITE CONDITIONS

Since bedding shear zone in the clay seam layer is considerably thin, excessive pore water pressure can be dissipated in a short time. The drained shear strength obtained from a constant-volume direct shear test with measurement of vertical stress change is considered applicable to the site condition (Ohta et al. 2010). Wangsa et al. (2012) and Pipatpongsa et al. (2011) examined the mechanical properties of G1 green clay which is associated with a bedding shear zone in Area 4.1. The residual friction angles with zero cohesion-intercept obtained from multi-stage reversal constant volume direct shear box test are ranged from 12˚ to 17˚. Therefore, the minimum value of 12˚ was considered as a critical case. Moreover, consideration of hydro-static pressure is required in engineering practice. Four cases are considered below.

A) Failure width of passive arching slope in dry condition

$$B_f = \frac{k}{\sin\alpha - \tan\phi_i \cos\alpha}\frac{\sigma_c}{\gamma} \quad (3)$$

B) Failure width of passive arching slope in dry condition with hydro-static pressure on bedding shear plane

$$B_f = \frac{k}{\sin\alpha - \left(1-\gamma_w/\gamma\right)\tan\phi_i \cos\alpha}\frac{\sigma_c}{\gamma} \quad (4)$$

C) Failure width of passive arching slope in fully saturated condition with no hydro-static pressure on bedding shear plane

$$B_f = \frac{k}{\left(1+\gamma_w/\gamma\right)\sin\alpha - \tan\phi_i \cos\alpha}\frac{\sigma_c}{\gamma} \quad (5)$$

D) Failure width of passive arching slope in fully saturated condition with hydro-static pressure on bedding shear plane

$$B_f = \frac{k}{\left(1+\gamma_w/\gamma\right)\sin\alpha - \left(1-\gamma_w/\gamma\right)\tan\phi_i \cos\alpha}\frac{\sigma_c}{\gamma} \quad (6)$$

As the last condition is the most critical case, Eq.(6) is employed to determine the failure width in the implementation at the site. Based on various laboratory and field experiments, the material parameters (EGAT 1985, 1990, Khosravi et al. 2011 and Wangsa et al. 2012) are selected for the analysis as summarized in Table 1. The contribution of the arching effect can be evaluated by a factor of safety. The safety factor for a two-dimensional slope (planar condition) is simply calculated by Eq.(7) and Eq.(8) for dry and submerged conditions, respectively. Based on Eq.(3) and Eq.(6), the factor of safety for three-dimensional slopes (arching effect condition) can be calculated by Eq.(9) and Eq.(10) for dry and submerged conditions, respectively.

Table 1. Geometry and material parameters of the green clay seam and shale required for calculating safety factor of the undercut slope.

Inclined slope, α	18°
Residual interface friction angle, ϕ_i	12°
Bulk unit weight of shale, γ	19.12 kN/m^3
Unit weight of water, γ_w	9.81 kN/m^3
Residual UCS of shale, σ_{cr}	0.33 MPa
Peak UCS of shale, σ_{cp}	4.50 MPa
Designed UCS of shale, σ_{cd}	1 MPa

UCS = unconfined compressive strength

Table 2. Calculated safety factors against a width 130 m for dry and submerged conditions under two and three dimensions using residual, peak and designed values of unconfined compressive strength of shale with an arching coefficient assigned to k_2=1.

Safety factor	2D (planar slope)		3D (arching effect)	
	dry	submerged	dry	submerged
Residual rock strength	0.6	0.2	1.2	0.4
Peak rock strength			16.9	4.9
Designed rock strength			3.8	1.1

$$SF_{2D,dry} = \frac{\tan\phi_i}{\tan\alpha}, \quad SF_{2D,submerged} = \frac{\left(1-\gamma_w/\gamma\right)\tan\phi_i}{\left(1+\gamma_w/\gamma\right)\tan\alpha} \quad (7), (8)$$

$$SF_{3D,dry} = \frac{k}{\sin\alpha - \tan\phi_i \cos\alpha}\frac{\sigma_c}{\gamma B} \quad (9)$$

$$SF_{3D,submerged} = \frac{k}{\left(1+\gamma_w/\gamma\right)\sin\alpha - \left(1-\gamma_w/\gamma\right)\tan\phi_i \cos\alpha}\frac{\sigma_c}{\gamma B} \quad (10)$$

Using the material parameters shown in Table 1, the safety factor determined from Eqs.(7)–(10) are shown in Table 2. In the calculation, the arching coefficient assigned to k_2=1 for mild slopes with supporting ground for the maximum exposed width 130 m. Safety factors based on a planar condition for both dry and submerged conditions are less than one which might conclude that the slope cannot be undercut. However, an arching effect allows a higher factor of safety; therefore, if the shale above the clay seam has not been weathered into weak soft rock, mining at Area 4.1 with the span of 130 m is possible. The undercut span at Area 4.1 is varied as a function of the unconfined compressive strength of the shale; thus, if the unconfined compressive strength of shale on the slope could be maintained at 1 MPa at the least, the undercut span of 130 m at the clay seam level can be reached safely in a short term.

The width of Area 4.1 in the Mae Moh lignite mine is about 300 m and the length about 250 m along the pit wall. The total depth of 33 m in this area for lignite mining was planned by digging 3 benches with a height of 11 m each. According to EGAT's mining plan, Area 4.1 is divided into 2 stages of excavation, namely stage 1 for 180 m and stage 2 for 120 m measuring at the G1 clay seam level which is located at a depth of 11−12 m. Stage 1 is subdivided into 1A and 1B. Despite a crack along the existing fault zone with a length of about 50 m, observed in May 2012 at the left side corner of the pit, the process of excavation and mining for stage 1A to a width of 120 m was successfully achieved over December 2011 to July 2012. At the end of stage 1A, the total movement towards the pit at the clay seam level measured by an inclinometer was 24 mm and the slope had already been mobilized along the bedding shear plane. For stage 1B, an increment width of 60 m was excavated during July to October 2012 across a rainy season, while the slope on the right side of the excavated pit was being dumped with overburden “claystone” from the pit up to 100,000 m^3 covering a length of about 60 m to provide a counterweight. Supported dump was on an incline plane, limestone rock bunds were constructed underneath dumped material for reinforcement. Due to excessive movement more than 60 mm in September 2012, the inclinometer tube was deformed and not functioning. Fig.6 shows the beginning of stage 1B observed in October 2012, when the total excavated width reached 190 m.

6 CONCLUSIONS

The slope stability problem in the Mae Moh lignite mine in Lampang province in Thailand has been briefly reported. The presence of a weak shearing zone in the clay seam between the layer the shale caused trouble in the northeast pit. Area 4.1 in the northeast pit is one of the potential failure slopes; part of the lignite and rock mass had been left in front of this slope as a counterweight to prevent a huge landslide. Mining in the unstable slope was considered expensive. The newly developed moving-pit mining method based on the physical model and theoretical developments was introduced as an applicable method for mining in Area 4.1. In order to apply this method, two stages of excavation were planned. The process of excavation and in-pit dumping must be done in sequence. At the clay seam level, the total excavated width of 190 m with an exposed width of 130 m and an area of dumped claystone of 60 m with limestone rock bunds underneath was found stable. It is concluded that this novel procedure for mining is practically realizable and results in reductions in massive excavation, transportation and dumping of unstable rock mass, as well as saving an amount of time and expense.

7 ACKNOWLEDGEMENT

This research work was funded mainly by the Electricity Generating Authority of Thailand (EGAT) under the research project grant “Stabilization of Alternative Excavations and Strengthening of Supporting Materials for Pit Wall in Area 4.1”. In addition, the financial support provided by JSPS KAKENHI Grant Numbers 23760441 and JSPS Asian CORE Program is truly appreciated. The authors would like to express their gratitude to all staffs of Mae Moh Geotechnical Department of EGAT and particularly acknowledge Mr. Prajuab Doncommul, EGAT and Dr. Cheowchan Leelasukseree, Chiang Mai University for their collaborations and contributions.

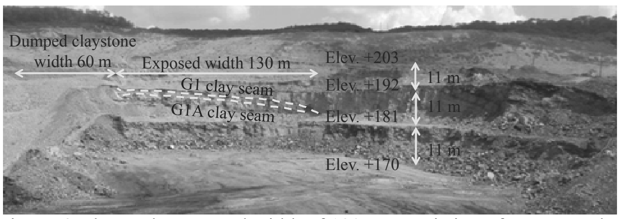

Figure 6. The total excavated width of 190 m, consisting of an exposed width of 130 m and an area of a dumped claystone of 60 m measuring at the level of clay seam (as of October 2012)

8 REFERENCES

EGAT 1985. *Thailand-Australia Lignite Mines Development Project*, Geotechnical Report, Mae Moh Mine, Thailand.

EGAT 1990. *Interim Review of Geotechnical Strength Data*. Mae Moh Mine, Thailand.

Janssen H.A. 1895. Versuche über getreidedruck in silozellen. *Zeitschr d Vereines deutscher Ingenieure* 39, 1045-1049.

Jenike A.W. 1961. Gravity flow of bulk solid. *Bulletin of the Utah Engineering Experiment Station* 108.

Khosravi M.H. 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, *PhD Dissertation*.

Khosravi M.H., Ishii Y., Takemura J. and Pipatpongsa, T. 2010. Centrifuge model test on compacted sand slopes undercut by In-flight excavator. *Proceedings of Geo-Kanto*, 136-139.

Khosravi M.H., Pipatpongsa T., Leelasukseree C. and Wattanachai P. 2009. Failure mechanisms in arched excavation of sloped earth using model test. *Proceedings of Geo-Kanto*, 241-246.

Khosravi M.H., Pipatpongsa T., Takahashi A. and Takemura J. 2011. Arch action over an excavated pit on a stable scarp investigated by physical model tests. *Soils and Foundations* 51(4), 723-735.

Khosravi M.H., Pipatpongsa T., Takemura J., Mavong N. and Doncommul P. 2011. Investigation on shear strength of shale at the Mae Moh open-pit mine, *Proceedings of the 4th Thailand-Japan International Academic Conference*, 51-52.

Khosravi M.H., Tang L., Pipatpongsa 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* 6(2), 193-205.

Ohta H., Pipatpongsa T., Heng S., Yokota S., Takemoto M. 2010. Significance of saturated clays seams for the stability of rainfall-induced landslides. *Bulletin of Engineering Geology and the Environment* 69(1), 71-87.

Pipatpongsa T., Khosravi M.H., Doncommul P. and Mavong N. 2009. Excavation problems in Mae Moh lignite open-pit mine of Thailand. *Proceedings of Geo-Kanto*, 459-464.

Pipatpongsa T., Heng S., Likitlersuang S., Mungpayabal N. and Ohta H. 2011. Investigation of mechanical properties of clay seam in bedding shears of the Mae Moh open-pit mine of Thailand, *Proceedings of the International Conference on Advances in Geotechnical Engineering*, 209-214.

Terzaghi K. 1936. Stress distribution in dry and saturated sand above a yielding trap-door. *Proceedings of First International Conference on Soil Mechanics and Foundation Engineering*, 307-311.

Walker D.M. 1966. An approximate theory for pressures and arching in hoppers. *Chemical Engineering Science* 21 (11), 975-997.

Walters J.K. 1973. A theoretical analysis of stresses in axially-symmetric hoppers and bunkers. *Chemical Engineering Science* 28(3), 779-789.

Wangsa R., Wongsiriworakul J., Mungpayabal N., Pipatpongsa T. and Wattanachai P. 2012. Residual shear strength of Mae Moh clay seam measured by multiple reversal direct shear box test under constant load, *Proceedings of the 17th National Convention on Civil Engineering*, GTE012, 1-10.