MINING SYSTEM AND DESIGN FOR DEVELOPMENT OF UNDERGROUND COAL MINE FROM OPEN-CUT HIGHWALL FOR THICK COAL SEAM

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MINING SYSTEM AND DESIGN FOR DEVELOPMENT OF UNDERGROUND COAL MINE FROM OPEN-CUT HIGHWALL FOR THICK COAL SEAM

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ABSTRACT

The surface mining method is generally considered to be more advantageous than the underground method, especially in recovery, grade control, production capacity, economics, flexibility, safety and working environments. Therefore, the surface mining method is not only common in major coal producing countries, but it other ones as well. However, surface mine conditions are worsening each year: the stripping ratio is increasing, approaching economic ratio, the regulation of environmental protection, and poor infrastructure for coal from inland mining areas. To meet the demand for coal in Asian countries, and the rest of the world, underground mines have to be developed in the near future. Under these circumstances, the development of new coal mines from open-cut highwall are being planned in several mines in Southeast Asian countries including Thailand, Indonesia, etc. Moreover, some of the Southeast Asian mines have thick coal seams. However, if the conventional mining systems and designs introduced in US, Australia and European countries are applied, several geological issues can be expected due to the mines’ weak geological conditions. From these backgrounds, a mining system and design for development of underground coal mines from open-cut highwall especially for weak and thick coal seams have been proposed in this study.

In order to study mining system and design for development of underground from open-cut highwall for weak-thick coal seams, Mae Moh Mine in Thailand was chosen as a research site. Firstly, the criteria for the applicability and the design of the single to multi-slice extraction method at the transition area from surface to underground mines for different pit depths and thickness of coal seams under strong and weak geological conditions were studied by means of “FLAC3D” finite difference code. The numerical models with 200 m, 300 m and 400 m pit depths are considered for modeling purpose and application of longwall/shortwall mining system is considered the extraction methods due to their safety and high productivity. Based on the results, appropriate mining method and design of boundary pillars, barrier pillars and panels for different mining depth, different thickness of coal seams under weak and strong geological conditions are investigated and discussed. From the results of the single-slice method with a 3 m mining height, it was found that the conventional longwall mining method can be applicable at the transition area from open pits to underground mines under weak geological conditions. However, the results represent that the deeper the pit depth, the more stress concentrates around the
toe of the slope and is more significant in weak geological conditions. It is found that
the panel width of 300 m and a boundary pillar width of 100 m are appropriate in all
the pit depths of 200 m, 300 m and 400 m in strong geological conditions. However,
it is a boundary pillar width of 150 m in a 400 m deep pit is required; although, a
pillar width of 100 m is appropriate in 200 m and 300 m deep pits under weak
geological conditions. For the extraction of thick coal seams using the multi-slice
longwall/shortwall top coal caving method, the slope stability problems are not
expected to be under strong geological conditions, even if the panel width of 300 m
is applied and boundary pillar width of 100 m is sufficient for all the mining depth
conditions. On the other hand, it was found large impact on the slope stability and
many geotechnical issues including slope failures, large ground subsidence and large
failures around the panel and pillar occurred under weak geological conditions when
a panel width 300 m is applied. As the results, a small panel width of 100 m is
appropriate in 200 m and 300 m deep pit, but 60 m for 400m deep pit. The boundary
pillar widths for the 200 m and 300 m deep pits are 100 m and 200 m, but for the 400
m deep pit, a boundary pillar width of 200 m, panel width of 60 m, and an inter-panel
pillar width of 100 m is required in order to maintain the stability around the
transition area from open pit to underground mine. In order to increase the coal
recovery and improvement of stability of slope, application of the multi-slice
longwall/shortwall top coal caving in conjunction with stowing is proposed and
discussed. Stowing had proved to be quite effective in reducing the subsidence at the
slope, as well as reducing the failures around the panel and pillars and maximizing
the coal recovery. As the results, a panel width of 100 m can be designed for all the
pit depths if stowing is applied and the boundary pillar widths for 300 m and 400 m
deep pits are 100 m and 200 m, respectively.

After that, applicability of multi-slice longwall/shortwall top coal caving method
and a suitable design of the mining method for the transition area at the Mae Moh
Mine, which has the an extra-thick coal seam under a weak geological condition, are
investigated based on the results and design criteria for weak-thick coal seams.
According to the results, since the coal seams are too weak and the open-cut highwall
are very large, longwall mining might not be feasible at the transition area from the
open pit to the underground mine, even if the stowing is applied. Large slope failures
occurred even though a subsidence of about 5 cm is observed at the slope. According
to the results, it is found that a short wall with the length of 30 m and immediate
stowing after panel extraction is more appropriate at the transition area from the open
pit to the underground mine in order to control the slope failures, as well as subsidence, in the Mae Moh Mine. It was also found that a boundary pillar width of 200 m is appropriate, and the two-slice extraction can safely be applied at the transition area in conjunction with stowing method.

Finally, alternative methods of mining in conjunction with stowing for the weak and extra-thick coal seams at the deeper site of the highwall at the Mae Moh Mine are proposed. The application of the multi-slice longwall top coal caving method and multi-slice bord-and-pillar method, in conjunction with stowing, for mining the weak and extra-thick coal seams at the deeper sites of open-cut highwall is investigated and discussed. According to the results, it was found that multi-slice longwall top coal caving with temporary supports and a stowing system, as well as multi-slice bord-and-pillar mining with an alternative method for the cutting and stowing system, can be employed for the weak and extra-thick coal seams. These are effective methods for diminishing ground disturbance and subsidence in order to improve mine safety and to maximize coal recovery.
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January, 2014
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CHAPTER 1
INTRODUCTION

1.1 Background

Surface mining method is generally considered to be more advantageous than underground method, especially in recovery, grade control, production capacity, economics, flexibility, safety and working environments. Therefore, surface mining method is more common in several major coal producing countries, such as Australia, US, India, Indonesia, Russia, and South Africa. Surface mining accounts for around 80% of production in Australia; 67% in USA, 99% in Indonesia, and 81% in India (World Coal Association, 2013; Matsui et al., 2001). However, surface mining is typically faced higher stripping ratio as the mine gets deeper. As several open pits have been exploited over many decades, nowadays many open pit mines are being suffered from high extraction cost. Many open pit mines have been already stopped operation due to the uneconomic stripping ratio value and it has been considered recovery of remaining coals by other methods or abandoned. Highwall mining systems using an auger machine or a continuous miner have been applied to recover remaining coal deposits from final highwall of open pits in some coal mines in US, Australia, India and Indonesia. The auger system is only suited for the short length coal deposits. The auger machine can excavate about 150m long and 1-2m in diameter (Vandergrift, et al., 2004). The continuous highwall mining systems can provide safe operation and high productivity. The continuous miner can reach about 500m or more into the wall (Matsui et al., 2001). However, the applicabilities of highwall mining systems are also limited. Highwall mining systems are suited for relatively flat coal seams. It is difficult or almost impossible to apply the system in steeper dip coal seams, over 15° (Matsui et al., 2001). In addition, they cannot be applied under poor strata conditions and high stress conditions due to pillar and roof failures (Matsui et al., 2004). Due to the limitations of highwall mining systems, several coal mines have been attempted to adopt conventional underground mining methods, such as room and pillar and longwall methods, to recovery remaining coals from highwall. Beltana Mine in Australia has been tried a highwall access longwall punch mine, which achieved its first full year of operation in 2004, producing 6 Mt (ROM) coal (Mining Journal, 2008). It has also been tried underground operations from final highwall in Indominco coal mine and Satui mine in Indonesia. However,
due to the problems in roof collapse and concerns about the ground control issues, the underground mine projects have been stopped. To meet the demand for coal in Asian countries, and the rest of the world, underground mines have to be developed in the near future. Under these circumstances, the development of new coal mines from open-cut highwall are being planned in several mines in Southeast Asian countries including Thailand, Indonesia, etc. Moreover, some of the Southeast Asian mines have thick coal seams. However, since mining method and design for development of underground mine from highwall for thick seams under weak geological conditions have not well developed so far, mining companies are being concerned about geotechnical issues and none of them has started underground operations until now. Therefore, it is great important to develop a mining method and design guidelines for development of underground mine from open-cut for thick seams under weak geological conditions for South-east Asian countries to meet the coal demand not only for local but also for the rest of world.

1.2 Literature Review

When an underground mine is developed from open cut highwall, it is essential to retain and maintain slope stability through the life of underground mining. In this case, selection of mining method plays an important part. According to the current available underground mining technologies, we can consider the following mining systems for thick coal seams:

(1) Multi-slice bord and pillar method
(2) Blasting gallery method
(3) Extended height longwall method
(4) Multi-slice longwall method
(5) Longwall top coal caving method

Bord-and-pillar method has some advantages: it is simple and flexible method; it requires relatively lower capital investment compared with longwall method. In international bord and pillar mining practices, thick coal seams are mined by multi-slice method, and the thickness of each slice varies 2-4m. This method is also effective to control surface features and subsidence. But, the prominent disadvantage is that coal recovery percentage decreases rapidly with increasing depth, because the
size of pillars has to be increased to prevent pillar failures and strata control problem. In some deep coal mines, the extraction ratio is less than 40%. And also, according to the bord and pillar practices in Indian coal mines, when three or more slices is applied in extra-thick seams, pillars extraction become difficult due to the strata control problems (Singh, 1987).

![Typical layout of bord and pillar mine](image)

**Figure 1.1** Typical layout of bord and pillar mine

In recent years, blasting gallery method (BGM) was tried for thick coal seams in some southern Indian coal mines. The BGM was designed by Charbonage de France (CdF) mining enterprise though this method was not actually tried in France for pillar recovery. Basically this method comprises splitting of the pillars, drilling of a ring of shotholes simultaneously using milli-second delay detonators. The coal thus blasted is cleared by remotely controlled LHDs (Load-Haul-Damp Vehicles) and the goaf is allowed to cave. This method requires substantially less investments than those required for longwall method. This method allows mining of thick seams about 7.5 m of thickness in one pass. This method offers high percentage extraction ratio (in excess of 70%). The mining operation and mechanism of this practice in weak geological condition have not been known clearly.

Among the underground methods employed in coal mining, longwall method is claimed to be the highest productive and the safest method. Longwall mining is a high extraction coal mining technique where coal is removed in large underground
blocks or panels. Extraction by longwall mining is an almost continuous operation involving the use of self-advancing hydraulic roof supports, a sophisticated coal-shearing machine, and an armored conveyor paralleling the coal face and it allows the coal to be mined, collected, and hauled out of the mine with minimal amounts of delay. Generally, coal seams about 2-4 m thick has been mined by conventional single pass method. But, due to the recent advent of technology in shield support, thick seams are also operated by a single pass method in some parts of the world. The current highest shield support has a 7.5 m in maximum height (Bucyrus, 2009). However, the extending the height of a conventional single pass longwall has some limitations such as equipment size, weight and stability, coal seam properties and face conditions (Ozfirat, M. K., 2005; Heblewhite B.K., 2005).

![Figure 1.2 Typical longwall mining operation](image)

For thick coal seams, it can also be considered the multi-slice longwall method, where the coal block is divided into multi slices and each slice is extracted by conventional longwall method. The thickness of individual slice may vary from 2 to 4 m depending on the local characteristics of the coal seam. There are a number of multi-slice techniques which have been used over the past two decades and these can be summarized as follows:
(1) Simultaneous slicing method
(2) Non-simultaneous slicing method

Simultaneous slicing is the method where extraction of all slices advances simultaneously and the cross sectional position of the extraction faces is in a stagger pattern, where the first slice (the uppermost one) has an advanced position in relation to the slice which follows and the faces are usually less than 55 m apart (Jeremic, 1985). Simultaneous slicing by longwall mining is the most common method for extraction of coal seams, of up to 10 m thickness i.e., in which a maximum of three slices can be delineated. Success of this method depends on the homogeneity and strength of coal seams as well as on the readiness of the roof strata to cave (Jeremic, 1985). In many of simultaneous slicing practices, wire meshes are used for artificial roofing and preventing coal dilution. For example, while mining the first slice (the uppermost slice), face extraction is followed by laying of wire mesh on the mine floor in order to form an artificial roof for the second slice. The second slice extraction then follows several tens of meters behind the first slice under the wire mesh. The wire mesh is laid down onto the floor of the second slice and it forms an artificial roof for the next slice again (see Figure 1.3). In this practice, however, manual laying of wire mesh is a labor-intensive operation, and it delays face progress, resulting in poor productivity. Moreover, spontaneous combustion sometimes occurs in the gob area, particularly when the coal remnants in gob are very susceptible to

Figure 1.3 Simultaneous multi-slice longwall mining with artificial roofing by wire mesh
self-ignition. In some mines, mud injection into the gob is applied for preventing or extinguishing spontaneous combustion. This mud injection also improves the formation of a regenerated roof for a next slice and reduces the period required for regeneration (Matsui et al., 2010). If the geological and geotechnical conditions are appropriate, this practice of mining is very economical and can offer high productivity. However, since this is a method of full face mining of thick seams, large caving of roof strata are occurred and ground disturbance caused by this practice is usually large. Thick coal seams have also been mined by non-simultaneous slicing techniques in some parts of the world. Depending on the order of slicing, it can be categorized as: (1) non-simultaneous ascending and (2) non-simultaneous descending.

In the ascending practices, the extraction is begun from the base of the coal block along the mine floor and the next slices are extracted above the mine-out slices.

Figure 1.4 Variations in multi-pass longwall mining practices
sequentially in ascending order. In this order of slicing method, caving is excluded and stowing to the mined-out void is always required since the extraction of next slice is impossible if without stowing due to subsequent coal deformation in the upper adjacent area after extracting lower slice (Jeremic, 1985).

In descending practices, the extraction is begun along the mine roof and the next slices are extracted sequentially in descending order. In this practice, caving is allowed and it can have the roof support for the lower face, such as artificial roof, rock parting or coal parting between the slices similar to the simultaneous practices. This method has been employed in several coal mines (eg., in Europe and Japan).

In the practice of non-simultaneous slicing, it is necessary to have a separate entry for each slice, which results increasing in development costs. However, the productivity is relatively higher and ground disturbance caused by these methods are less than simultaneous slicing because each slice is extracted independently and each can advance in its own pace. Therefore, it might be possible to apply the system in a transition if conditions are appropriate for adoption of these practices.

Currently both the ascending and descending practices are in use. However, considering advantages and disadvantages of both these practices, the descending order of slicing with caving is preferred to ascending order of slicing wherever the conditions are suitable for adoption of these practices. The prominent advantages of descending order of slicing are the possibility of working thick seams with caving and low risk of spontaneous heating (Singh, 1997).

Another method of longwall mining in thick seam is longwall top coal caving (LTCC), which is a modified longwall method where coal block (about 2-3 m) is cut conventionally at the base of the seam and the additional coal is recovered by fracturing of above top coal by front abutment pressure and allowing it to fall via controllable caving shields on a rear armored face conveyor (AFC) that is mounted at gob-side. The method allows mining of thick coal seams about 5 to 12 metres in single pass, generating high productivity and economic returns for an operation (Yancoal, 2013). The LTCC shield support system was first applied in Russia in the 1940s and then subsequently introduced in France in the late 1980s. The LTCC method allows for up to 90% recovery of additional coal that is usually unmineable.
using conventional longwall extraction. However, in some cases, coal recovery is less than expected due to coal seam and strata conditions. Operational issues also limit top coal recovery and can often account for a greater percentage of the reduce recovery than geological conditions alone. Therefore, in practical situation, about 60% of additional coal can be recovered. The technology has been successfully implemented in a number of mines in China and it has extensively introduced in some other countries, e.g., in Australia and Turkey (Austar Coal Mine, 2013; Hebblewhite, 2005) considering the Chinese geological and geotechnical conditions. However, it must take account of the potential problems, such as methane gas and coal dust explosions, spontaneous combustion, wind blast in the gob and severe subsidence, in its application (Matsui, 2010).

Although longwall mining provides high productivity and safe working conditions in underground mining, there has often been experienced with the problems at the surface due to subsidence. Several mining and geological parameters affect the magnitude and extent of subsidence. Rock mass, geological structure, in situ stresses, and mining method are the key factors influencing surface subsidence. Several types of subsidence deformations caused by longwall mining are discussed by Shadbolt (1978) and Whittaker and Reddish (1989). The overlying strata experiences stress re-distributions as a result of the longwall mining is illustrated in Figure 1.6. Continuous or trough subsidence forms as a gentle depression over a large area. Material over the central part of the mined void moves vertically downward at the same time as material from the adjacent sides moves toward the
centre and downward.

The basic ground movements developed for surface trough subsidence are:
- vertical subsidence or vertical displacement,
- horizontal displacement,
- tilt or slope, i.e., the derivative of vertical displacement with respect to the horizontal (differential subsidence),
- horizontal strain (extension and compression), i.e., the derivative of horizontal displacement with respect to the horizontal,
- vertical curvature (differential tilt), which may be approximated by the derivative of the slope or the second derivative of the vertical displacement with respect to the horizontal

The effect of trough subsidence caused by longwall mining under slope on slope stability are discussed by Whittaker and Reddish (1989). Figure 1.7 shows the subsidence initiation and trough development in respect of longwall extraction under slope and thereby inducing a state of instability which results in the slope sliding and collapse and underground mining cannot be continued. Therefore, it must be paid careful attention impact of subsidence and its subsequent effect to the slope stability when the longwall method is applied in a transition from open pit to underground
mine. In this case, the design of safety pillars such as boundary pillar and inter-panel pillar and panels in the transition area play important parts to control the subsidence at the slopes. However, there are still no standard guidelines for design of panels and pillars at the transition area for weak geological conditions. Furthermore, there are no standard guidelines to evaluate behavior of slopes and overall slope stability for weak geological conditions so far. Therefore, the application of longwall method in the transition area for coal seams under weak geological conditions still remains a challenge.

With the advancement in computer capabilities and growing interaction between computational mechanics, numerical modeling tools have enabled a greater potential in advanced understanding of complex geotechnical problems. In academic research and in engineering practice, the numerical approaches continuum modeling and discontinuum modeling have gained wide popularity. Discontinuum method is well suited for rock mass where high density of discontinuities (e.g., joints) exists and plays significant role on the geotechnical behavior of the rock mass. However, higher expertise is needed to build up a representative model by discontinuum codes and the computing time takes much longer in comparison with that takes in
continuum codes. Continuum modelling is well suited for the analysis of rock formations that are comprised of massive, intact rock, weak rocks, and soil-like or heavily fractured rock masses. However, most continuum codes also incorporate a facility for including discrete fractures such as faults and bedding planes that can be modeled individually. The continuum approaches used in geotechnical problems include the finite-element and finite-difference methods. In finite element method, the problem domain is discretized into a limited number of elements that are connected at nodal points. The stress-strain relationship is defined by an appropriate constitutive law. The stress, strain and deformation to be analysed are caused by change in the subsurface condition (e.g. excavation). Stress, strain and deformation induced in one element impacts the behavior of its neighbor elements and so forth. The analysis is performed by solving the equation matrix that models the mesh. The finite element method uses implicit solution technique and requires large computing capacity. The finite difference method is similar to finite element method where problem domain is discretized into a set of sub-domains or elements. However, in finite-difference method (FDM), solution procedure is based on numerical approximations of the governing equations, which are the differential equations of equilibrium, the strain displacement relations and the stress-strain equations. In finite-element method (FEM), the procedure may exploit approximations to the connectivity of elements, and continuity of displacements and stresses between elements (Eberhardt, 2003). The advantage of finite difference method over finite different method is that since no matrices are formed, the required processing and storage capacity of the computer is small. Among the finite difference codes, FLAC3D codes is being increasingly used in rock engineering research due to its powerful built-in features and capabilities to solve complex problems in rock slope/underground mining. FLAC3D contains an automatic 3D grid generator in which grids are created by manipulating and connecting predefined shapes. It incorporates the facility to model any shape of the objects. FLAC3D embodies special numerical representations for the mechanical response of geologic materials. The program has eleven basic built-in material models: the “null” model; three elasticity models (isotropic, transversely isotropic and orthotropic elasticity); and seven plasticity models (Drucker-Prager, Mohr-Coulomb, strain-hardening/softening, ubiquitous-joint, bilinear strain-hardening/softening ubiquitous-joint, double-yield and modified Cam-clay). Each model is developed to represent a specific type of constitutive behavior commonly associated with geologic materials. Either velocity (and displacement) boundary conditions, or stress (and force) boundary conditions,
may be specified at any boundary orientation. Initial stress conditions, including gravitational loading, may also be given. All conditions may be specified with gradients. The explicit, Lagrangian, calculation scheme and the mixed-discretization zoning technique used in FLAC3D ensure that plastic collapse and flow are modeled very accurately. A factor of safety can also be calculated automatically for any FLAC3D model composed of Mohr-Coulomb material and the calculation is based on a “strength reduction technique”. In addition, FLAC3D also contains a powerful built-in programming language FISH, which can be used to customize the model for specific requirements. These features are desirable in modeling an open pit/underground mine and implementing the objectives of our research.

1.3 Objectives of the Research

To meet the great demand for coal in Asian countries and the rest of the world, underground mines have to be developed in the near future. In South-east Asian countries, almost all of the coal is extracted from open pit mines. For example, in Indonesia, over 300 million tons of coal are produced annually and 99% of the total production of coal is from open cut mines. Therefore, there are many sites where mining operations have developed long highwalls that have been abandoned. In addition, due to the surface mine conditions are worsening each year: the stripping ratio is increasing, approaching economic ratio, the regulation of environmental protection, and poor infrastructure for coal from inland mining areas, there are many problems to expand the current open-cut mines and exploit new ones. Under these circumstances, the development of new underground coal mines from open-cut highwalls are being planned in several mines in Southeast Asian countries including Thailand, Indonesia, etc., in order to meet the great demand for coals in the future. However, guidelines for mining method and design for underground mining from open-cut highwall for weak geological conditions are not well developed. In addition, some of the South-east Asian mines have thick coal seams and thus several geological issues can be expected if the coal seams are mined by conventional method applied in US, Australia and European countries. From this background, the primary objectives of the research is to develop mining method and standard mine design for the transition from open pit to underground mine under weak geological condition, particularly for thick coal seams.
In order to meet the study objectives, the Mae Moh coal mine in Thailand was chosen as a representative research site and appropriate mining method and design in transition area from open pit to underground mine as well as applicable underground methods for weak and extra thick coal seams at the deeper sites of final highwall in the Mae Moh coal mine are studied using the powerful FLAC3D finite difference code and proposed in this dissertation.

1.4 Outline of Thesis

The dissertation is organized by 6 chapters.

Chapter 1 introduces the background of this research, geotechnical issues and mining technology related to this research topic and an involved outline of the dissertation.

Chapter 2 describes the research site conditions of this study in Mae Moh Mine, Thailand and introduces the multi-slicing mining method with a stowing system for weak-thick coal seams. Moreover, the concept of punch mining and highwall mining systems are also discussed for their applicability of transition area from surface to underground mines in this chapter.

Chapter 3 describes the mining method and mine design for the transition area for weak and thick coal seams. In order to understand behavior of ground/slope under different situations and to investigate appropriate mining method and design approach for weak and thick coal seams, a series of numerical simulations were conducted modeling with different thicknesses of coal seams under different depths and geological conditions using “Flac3D” finite difference code. Based on the results, appropriate mining method and design of boundary pillars, barrier pillars and panels for weak and thick coal seams are discussed in this chapter.

Chapter 4 discusses applicability and a suitable design of the mining method proposed in Chapter 3 for the transition area at the Mae Moh Mine which has the an ultra-thick coal seam under a weak geological condition.

Chapter 5 discusses and proposes an alternative method of mining in conjunction
with stowing for the weak and extra-thick coal seams at the deeper site of the highwall at the Mae Moh Mine. In this chapter, application of the longwall method and bord-and-pillar method, in conjunction with stowing, for mining the weak and extra-thick coal seams at the deeper sites of open-cut highwall is investigated and discussed.

Chapter 6 concludes the results of this study.

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CHAPTER 2
RESEARCH SITE CONDITIONS AND AVAILABLE TECHNOLOGIES IN EXTRACTING COAL FROM OPEN-CUT HIGHWALL

2.1 Research Site Conditions

In this study, Mae Moh Mine, which is being planned to develop underground mine from final highwall, is chosen as a representative mine to study appropriate mining method and design for the transition from open pit to underground mine in weak and thick coal seams. Mae Moh Mine is located at latitude 18° 18' 21'' N, longitude 99° 44' 02'' E, about 630 km north of Bangkok, and 30 km east of Lampang city, in Thailand and it is owned by EGAT (Electricity Generating Authority of Thailand). Due to the high ash and sulfur content, the quality of Mae Moh coal is classified as lignite to sub-bituminous C in rank (Ratanasthien, 2008).

![Figure 2.1 Location of Mae Moh Mine](image-url)

The total geological and economical lignite reserves of Mae Moh Mine are approximated to be 1,140 million tons and 825 million tons, respectively. The annual production is about 16 million tons, which represents 70% of the total coal production of Thailand. About 347 MT of lignite has been produced, and the remaining future reserve is approximately 478 MT as of 2011. All of the lignite produced from the mine is supplied to the Mae Moh power plant which is located...
nearby the mine. The total generating capacity of Mae Moh power plant is 2,400 MW and it is fulfilling 15% of the total electricity demand of Thailand. The sharing ratio of electricity generated from Mae Moh power plant to all parts of Thailand is shown in Figure 2.2(b).

![Mae Moh power plant](image1)

![Sharing ratio](image2)

**Figure 2.2 (a) Mae Moh power plant and (b) Sharing ratio of electricity generated from Mae Moh power plant to all parts of Thailand**

### 2.1.1 Geological Condition

The Mae Moh coalfield is the largest tertiary coal deposit in Southeast Asia. The basin is bounded mostly by marine Triassic rocks of Lampang Group which are composed of limestone, shale, and sandstone (Ratanasthien, 2008). The Tertiary sequences of Mae Moh basin are divided into three main formations, namely Huai Luang(HL), Na Khaem (NK) and Huai King (HK) formations (see Figure 2.3). The HL formation mainly consists of red to brownish-red semi-consolidated and unconsolidated clay, silt and sandstone. NK formation composes lignite seams and gray to greenish-gray claystone and mudstone, whereas HK formation consists of semi-consolidated fine to coarse sandstone, claystone, mudstone and conglomerate with green, yellow, blue and purple in color. It is found five major lignite seams marked as J, K, Q, R and S seams in the NK formation and they are deposited in
various depth up to 600 m from surface. However, R and S seams are considered uneconomical due to being deep-seated and thin. In addition, the upper-most seam, J, which is composed of thin, laminated and fragmented coal beds, is also considered not very economical and thus economically attractive seams at Mae Moh basin are only K and Q seams. The thickness of K and Q seams range from 20 to 30 m and the interburden between the seams ranges 20 to 25 m. The cross section of Mae Moh basin showing the distribution of K and Q seams is presented in Figure 2.4. Most strata and coal seams at the Mae Moh basin are dipping 10-15 degrees towards the center of the basin.

Figure 2.3 Generalized stratigraphic column of Mae Moh Mine

Figure 2.4 Cross section of Mae Moh basin
Figure 2.5 Existing Mae Moh pit (Year 2013)

Figure 2.6 Final Mae Moh pit (Year 2047)
2.1.2 Mining Plan and Problem Statement

Currently, open pit operation is in progress and the total mining area covers an area of 4 km by 7 km at various depths up to 290 m (see Figure 2.5). According to the report of EGAT, the pit will be reached the depth of 500 m from the surface in the year 2047 and open pit operation will be finished at that time. (The final pit design of Mae Moh Mine is illustrated in Figure 2.6). However, as considerable lignite reserves will be remained around the final highwall, when the final pit limit is reached and open pit operation is finished. Therefore, EGAT is planning to extract the remaining lignite deposits around the final highwall by underground method in order to extend the life of the power plant of power plant another 10-15 years and to continue supply of coals from Mae Moh mine. Firstly, the lignite reserves about 160 Mt is targeted to extract by underground method as shown in Figure 2.6 and 2.7.

However, since the geological conditions at the Mae Moh Mine are weak and coal seams are extra-thick, and final highwall will be very huge, engineers are concerned about the geotechnical issues including slope stability and strata control
issues in underground mining. Therefore, the possibilities of underground mining and an applicable underground mining system are still being investigated.

2.2 Available Technologies in Extracting Coal from Open-cut Highwall

Currently, highwall mining systems including auger system, Metec highwall mining system and continuous highwall mining system have been applied to recover remaining coal from open pit slopes due to the advantages of enabling faster recovery of additional recovery of coal without removal of overburden. Auger system is primarily used where conventional surface or underground methods are not economically or technically feasible. The auger machine can excavate holes about 150 m long and 1-2 m in diameter (Vandergrift, et al., 2004). Development of an augering operation is relatively straight-forward. Continuity, uniform seam thickness and near- horizontal orientation (less than 10°) are essential for this technique (Mccarter & Smolnikar, 1992). According to recent estimates, there are about 150 auger systems in US coal mines and about 100,000 tons of coals are produced by auger mining each year (Zipf, 2005). In Australia, about 4.5 Mt of coals has been produced by single augers and about 0.35 Mt by twin augers (Adhikary, 2002). Although simple, augering machines have several inherent drawbacks that limit their effectiveness. Guidance is difficult, because the auger string consists of segments or flights and is, therefore, not rigid. Auger holes tend to drift downward and in the direction of rotation. This makes staying in seam a challenge, and hole penetration is

Figure 2.8 Auger system
often limited by intersection with the roof or floor. Penetration is also limited by the horsepower of the drive system at the highwall (Vandergrift, et al., 2004). Augers also suffer from increasing size degradation with depth, a fixed cutting height and certain other operational attributes that diminish the percentage of coal actually recovered (Matsui et al., 2001).

The Metec highwall miner uses a cutting head and gathering pan from a conventional underground continuous miner to feed a string of enclosed augers which are added as the miner advances forward. A push beam is used to force the cutting head forward from an outside platform. Conveyors transfer the coal from the auger to the platform and onto a stacking conveyor. When originally introduced, this system had improved productivity rates compared to the auger system. However, this system has become less popular due to the improvement in auger system. Applying the force through the push beam over long distances is a major disadvantage to this system, limiting the penetration depth (Schafer, 2002).

Highwall mining with continuous miners are being used to recover coal from open pit slope in some major coal producing countries, such as US, Australia and India. The continuous highwall miner - addcar system provides a cost-effective and safe means of extracting coal from final open pit highwalls and purpose-built trenches, and is ideally suited to applications that have 500 m or more of exposed highwall (Matsui et al., 2001). The system uses a continuous miner and addcars, which use conveyors to remove coal from the entry, to extract the seam from the highwall. As the continuous miner extends deeper into the highwall, additional addcars are added to the string, to enable the continuous miner to reach the desired depth. When this depth is reached and the coal on the conveyor is removed to the
dump trucks or stockpile, the individually powered addcars added on to the string, are then, one by one, decoupled from the string, until the continuous miner is extracted from the hole. The process can then restart on a new hole and the whole process is then repeated. The system can currently handle seams ranging from as low as 0.97 m to as high as 5.2 m in thickness. One week of production by a five-person crew (four crews) can produce between 20,000 and 30,000 tons of coal (Matsui et al., 2001). Currently there are about 30 addcars systems in US and the production is approximately 1Mt every year (Zipf, 2005).

The newest innovation in highwall mining comes in the form of the Archveyor. This mining system receives its cutting power from a highly modified Joy12CM continuous miner capable of cutting a 3.8 m-wide from 1.8 to 4.9 m thick. The Archveyor itself follows the miner into the heading, transporting the coal out. The Archveyor has drive units every 7.5 m, enhancing both vertical and horizontal flexibility. A chain conveyor is used for coal transportation and when lowered and reversed, to move the system forward. When mining is underway, hydraulic jacks lift the Archveyor clear of the ground allowing the conveyor to transport coal. (Walker, 1997). One week of production will produce over 30,000 tons of coal depending on the strata and mining condition (Matsui et al., 2001).

Although highwall mining can provide cost-effective and safe operation, sometimes geological conditions limits their effectiveness. It can only be able to
apply in the relatively flat coal seams with no fault. In steeper dip coal seams, over 15°, the operation becomes difficult or almost impossible to apply the system (Matsui et al., 2005). In addition, competent coal and immediate overburden is required. If the immediate overburden is not competent, coal may be left as roof. Besides, under poor strata and high stress conditions, highwall mining cannot be conducted due to pillar and roof failures. In such cases, punch highwall mining is more effective than the conventional highwall mining (Matsui et al., 2004).

Currently, bord-and-pillar and longwall methods are in use in recovering coals from highwall. Bord and pillar punch mining method has been applied primarily for shallow coal mining situations with limited overburden pressure. The advantages of this method are: simple and flexible system and requires a relatively low capital
investment. However, the disadvantage is that coal recovery percentage decrease rapidly with increasing depth, because the size of pillars has to be increased. To offset such low coal recovery it has been used mining with stowing in some mines.

Figure 2.12 Bord-and-pillar punch mining system (Matsui, 2012)

Figure 2.13 Longwall punch mining system
Rapid access longwall mining or punch longwall mining has been practiced in Australia. Australia's first punch longwall mining operation commenced in the late 1990s using conventional longwall equipment to mine coal from blocks developed directly from an open-cut final highwall (Australian Mines Atlas, 2013). Beltana is a highwall access longwall punch mine, which achieved its first full year of operation in 2004, producing 6 Mt (ROM) coal. It is considered to be the most cost-efficient longwall operation in Australia (Mining Journal, 2008). Broadmeadow Mine, operated by the BHP Billiton Mitsubishi Alliance (BMA), is another punch longwall which was commenced in 2005. About 3 Mt of coals are being produced every year by longwall punch mining method (Queensland mining industries, 2007). The advantages in this system of mining are: high productivity; the system requires no transport, conveyor drifts, shafts, complex ventilation systems or main headings as in conventional underground mining methods, hence this benefit provides cheaper, faster, simpler access and commencement of longwall mining. However, it is required proper mine planning and mine design to retain and maintain the open cut surface infrastructure throughout the life of underground operations. Due to its advantages of high production capacity and productivity, and competitively lower cost than highwall mining system, this system is expected to be increasingly implemented in Australian coal mines. However, the design and the ground behavior around the mining panel/face and its impact of the stability of slope and the mining operation in weak geological condition have not been made clearly.

2.3 Application of Multi-slice Top Coal Caving Method with Stowing

While considering the situation of Mae Moh Mine and applicability of current available mining methods for the transition area for Mae Moh Mine, applicability of highwall mining systems are less potential due to their limitations in penetration lengths. It is seen that punch highwall mining systems may be considered for the mine. However, as the coal seams are extra-thick at Mae Moh Mine, it must be mined by dividing the seams into multi-slicing. But, when multi-slicing method is applied, the ground behavior around the mining panel/face and their impact of the stability of slope and the mining operation have not been made clearly.

In Mae Moh mine, as the geological condition is very weak and coal seams are extra-thick, the problems in highwall instability and ground control issues are
expected if a conventional thick seam mining method is introduced. In order to cope with this problem, mining with stowing must be considered.

Stowing into underground mine void is common practice to reduce operational constraints and optimize recovery and safety. Mine waste rocks, by-products from power plants and industrials have been used throughout the world for many years as stowing material to provide additional support to underground excavations in mines. Generally, three stowing techniques are in use: solid stowing; paste stowing and hydraulic stowing. In solid stowing practices, stowing materials, such as mine waste rock, fly ash and other backfilling material are mixed together in proper proportion at the surface and then they are dropped through a vertical shaft down to a storage bin on the mine floor and transported to the longwall face by belt conveyer. At the face, they are moved to the gob by a scraper conveyer attached to the tail boom of the backfilling support. Finally, they are tamped with the rammer-compactor on the rear side of the support. As the coal face advances, mine waste rocks and fly ash are continually fed into the gob through the tail boom of the support (Yang, 2011). In paste stowing, waste materials are mixed with water and some additives such as Portland cement, lime, pulverized fly ash, and smelter slag and they are transported to underground mine voids by pipe lines. Currently, hydraulic stowing is the most advancing technique because it takes water as transport medium and it is easy to

![Diagram of solid stowing process](image)

**Figure 2.14 Concept of solid stowing (Yang, 2011)**
transport stowing materials to the underground void by using pump and pipe. In addition, since water makes underground cool down and it is also effective to prevent spontaneous combustion.

Considering the situation of Mae Moh mine, a new multi-slice top coal caving mining method based on the concept of punch longwall and top coal caving methods is proposed. The concept of the new multi-slice top coal caving mining method is illustrated in the Figure 2.15. First, the coal seam is developed along the mine roof with conventional cut. Then stowing material is injected into gob area in order to have better mine roof condition. After the stowing material is compacted, the next slice is begun by leaving appropriate thickness of coal parting beneath the first slice and it is recovered by applying a top coal caving method in the second slice. After the second slice is extracted using a top coal caving method, stowing material is injected into the gob area in the second slice. Next slices are also extracted by applying a top coal caving method and stowing is conducted after each slice is mined out and mining and stowing are repeated until the whole coal seam is mined out as the same manner. By applying this method, the number of slices required for the extra-thick coal seam and the burden for excessive costs for development of gateroads required for extra-thick seam (if conventional multi-slice mining method is applied) can also be overcome. And it will be also useful to reduce the impact on ground/slope due to extraction of extra-thick coal seams and can also be useful to

Figure 2.15 Concept of multi-slice top coal caving with stowing method
minimize the amount of waste management on surface. In the situation of Mae Moh Mine, there are many by-products from coal fired power plant that can be useful as stowing material. According to the EGAT’s report, about 3.6 million tons of coal ash and 2.1 million tons of gypsum are produced as by-products from the Mae Moh coal-fired power plant annually. From these by-products, only 60% of the coal ash (fly ash) is used as construction materials. The remaining 40% of the ash (clinker ash) and all the by-product gypsum are transported to the ash and gypsum dumping sites. 90-110 million BCM of overburden is removed annually. Therefore, if these by-products and the waste rocks are used as stowing materials, it can be less initial capital cost, it can reduce the problems for dumping the waste, and can also be useful for supporting underground mine. However, the detail investigations, including appropriate mining method, characteristics of stowing material and method and procedure of stowing etc., must be conducted prior to introducing the system to the mine.

2.4 Technical Issues for Multi-slice Longwall Mining from Final Highwall in Mae Moh Mine

As previously mentioned, the geological condition at the Mae Moh mine is very weak, coal seams are ultra-thick and final highwall will be very huge. Therefore, when the underground mine is designed and developed from open-cut highwall, special attention must be paid for the effect of the mining operation on the stability of the highwall as well as recoverable coal around the final highwall. In order to make the criteria for the applicability and the design of the multi-slice extraction method at the transition area from surface to underground mines for Mae Moh mine, firstly it is required to understand behavior of ground/slope and to make the criteria for the applicability and the design of the single to multi-slice extraction method at the transition area from surface to underground mines for different pit depths and thickness of coal seams under strong and weak geological conditions. Therefore, appropriate mining method and design of boundary pillars, barrier pillars and panels for weak and thick coal seams under different pit depths are investigated and discussed in this Chapter 3. Based on the design criteria for weak and thick coal seams obtained, applicability and a suitable design of the mining method for the transition area at the Mae Moh Mine are then investigated and proposed in the Chapter 4. And also, in Mae Moh mine as the coal seams are widely distributed into
the deeper sites of highwall, it is required to consider the suitable applicable method for those coal seams. Since the coal seams are weak and ultra-thick, alternative methods of mining must be sought. The applicable underground mining methods for the deeper site of Mae Moh final highwall are proposed and discussed in the Chapter 5.

2.5 Summary

The research site conditions are described, the applicability of currently available mining technologies for transition area from surface to underground mines for Mae Moh Mine are studied and discussed in this chapter. It is seen that auger system is simple and economic means of recovering coals when the reserves are not economically or technically feasible to underground mining. However, due to the limitation of auger length and the coal seams are widely distributed into the deeper site of Mae Moh mine, the auger system may not be feasible. Highwall continuous mining system provides safe and productive, but it cannot be applied under poor strata and high stress conditions due to pillar and roof failures problems. Therefore, applicability of highwall mining systems are less potential in the situation of Mae Moh Mine. It is seen that punch highwall mining systems may be considered for the mine. However, as the coal seams are extra-thick at the Mae Moh Mine, coal seams must be mined by multi-slicing. But, when multi-slicing method is applied, the ground behavior around the mining panel/face and their impact of the stability of slope and the mining operation in weak geological condition have not been made clearly. Considering the situation of Mae Moh Mine, the application of multi-slicing with stowing is also introduced. However, appropriate mining method/procedure of stowing method, etc, must be investigated prior to introducing stowing system to the mine.

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CHAPTER 3
DEVELOPMENT OF MINING METHOD AND DESIGN IN TRANSITION AREA FROM SURFACE TO UNDERGROUND MINE FOR THICK COAL SEAM

3.1 Introduction

When an underground mine is developed from an open-cut highwall, the design of panels and safety pillars such as boundary pillar and inter-panel pillar in the transition area have great influenced on the highwall stability as well as the amount of resource recovery around the transition area. If the panels are over-sized, it would cause large interaction between highwall and underground mine, that may result slope collapse or large subsidence at the slope surface. If the pillar sizes are inadequate, it is possible for slope instability or sliding of slope due to insufficient support to the highwall whereas if the pillars are over-sized, the amount of resource recovery around the highwall will be decreased. Therefore, careful planning and designing of panels and pillars around the transition area are great important when an underground mine is designed and developed from an open-cut highwall.

In order to make the criteria for the applicability and the design of the single to multi-slice extraction method at the transition area from surface to underground mine, the response of ground/slope under weak and strong geological conditions and under different pit depths; the relationship between size of panels/pillars and overburden depths, and the effect of number of slices and procedure of mining on slope stability are investigated using FLAC3D finite difference codes in this study. Based on the results, appropriate design of panels and pillars for conventional single slice and multi-slice mining under different thickness/depth under strong and weak geological conditions are proposed in this chapter. Due to the advantages of safety and productivity over other underground mining methods, application of longwall/shortwall mining method is primarily considered in extraction of coal around the transition area in this study.
3.2 Model Setup

Since there exist many deposits that extend from the shallow surface to considerable depths in South-east Asian countries, there are many deep open-cut mines (around 200 m in depth). However, the economically feasible stripping ratio is considered as 15-20 in maximum in most of the surface mining practices. Therefore, it is rarely found an open-cut mine which depth is more than 400 m. In this study, therefore, the depths of pits are basically considered as 200 m, 300 m and 400 m. The conceptual models with the different pit depths/geological conditions were constructed using the FLAC3D program in order to investigate responses of ground/slope and appropriate design of pillars and panels around the transition area for the different situations. The following sections will present the details about the models including geometry of models and finite difference grid, boundary conditions, initial stress field, constitutive behaviors and the properties of materials used in the analyses.

3.2.1 Model Geometry

In surface mining, as the bench design is usually based on economic reach of the mining equipment used in the mine, characteristics of deposit, production strategy and geological and geotechnical condition of the mine, etc., it is varied case by case.

Figure 3.1 Bench design adopted in the analyses.
Figure 3.2 Geometry, mesh and group of zones and dimension of the model (200 m depth)
In this study, therefore, the following assumptions are made based on the typical bench design for open-cut coal mining practices (Hem, P., 2012). The height of the each single bench is designed as 20 m, and the bench slope angle is 65 degrees. The width of the bench is set as 36 m whereas the safety berm is 6 m wide in the models. The angle of overall slope is 37 degrees. The details of the benches are illustrated in Figure 3.1. The width and length of the models were set far away from the areas to be excavated in order to avoid adversely effect of boundaries to the model results. The models are 700 m wide in y-directions and 1,000 m long in x-directions. Firstly, the response of ground/slope in conventional mining practices under different depths/geological conditions are investigated in this study and the thickness of coal seam is initially modeled as 3 m. The geometry, meshes and group of zones and dimension of the 200 m deep pit model employed in the analyses are illustrated in Figure 3.2.

3.2.2 Initial and Boundary Conditions

For initial stress field, the in-situ vertical stress is always computed as:

\[ \sigma_v = g \rho z \]  

(3.1)

where,
\( \sigma_v \) = In-situ vertical stress
\( g \) = gravitational acceleration;
\( \rho \) = average mass density of the overburden strata;
\( z \) = overburden thickness

And, in-situ horizontal stress can be estimated by the following expression:

\[ \sigma_h = k \sigma_v \]  

(3.2)

where,
\( \sigma_h \) = In-situ horizontal stress
\( k \) = the ratio of the average horizontal stress to the vertical stress;
\( \sigma_v \) = In-situ vertical stress
According to the previous study by Hoek & Brown, 1978, the ratio of the average horizontal stress to the vertical stress, $k$, varies widely from 0.5 to greater than 3.5 (Hoek & Brown, 1978). Since there can be a wide deviation of in-situ horizontal stress, using an estimated value does not represent realistic situations. Instead it may create unexpected results. In many cases where the in-situ horizontal stress is non-geotectonic, its role is not significant compared to other factors. In this study, therefore, the vertical initial stress component is assumed to increase as a function of overburden thickness, and horizontal stress is initialized directly through simple gravity loading. The horizontal displacement at the boundaries in x and y coordinate directions and the vertical displacement of the bottom of the models are assumed to be fixed in the model.

### 3.2.3 Constitutive Behavior and Properties of Materials

Mohr-Coulomb criterion is the most applicable criterion of failure for rocks in rock engineering field. Mohr-Coulomb parameters are usually available more often than other properties for rock mass. Therefore, Mohr-Coulomb plasticity model was applied in this study. It represents that a material yields when the subjected shear loading exceeded the shear strength of a material. The shear yield function $f^s$ is:

$$f^s = \sigma_1 - \sigma_3 N_\phi + 2c\sqrt{N_\phi}$$ \hspace{1cm} (3.3)

where,

$N_\phi = \frac{(1+\text{Sin}\phi)}{(1-\text{Sin}\phi)}$

$\sigma_1 = $ major principal stress

$\sigma_3 = $ minor principal stress

$\phi = $ friction angle

$c = $ cohesion

Shear yield is detected if $f^s < 0$ (tension is taken as positive number).

For the Mohr-Coulomb plasticity model, the following material properties are required:
(1) Density;
(2) Bulk modulus;
(3) Shear modulus;
(4) Friction angle;
(5) Cohesion; and
(6) Tensile strength.

In order to develop the design criteria under different geological conditions, two different mechanical properties of rock and coal are applied in the analyses. The mechanical properties for weak and strong conditions were determined by the data of laboratory tests for rock samples obtained from Thailand and Australian coal mines. Since FLAC3D uses bulk modulus and shear modulus instead of using Young’s elasticity modulus directly, bulk modulus and shear modulus were calculated using the following equations:

\[
K = \frac{E}{3(1-2\nu)} \quad (3.4)
\]

\[
G = \frac{E}{2(1+\nu)} \quad (3.5)
\]

where,
K = Bulk modulus
G = Shear modulus
E = Young’s modulus
\nu = Poisson’s ratio

3.3 Modelling Methodology for Underground Mining

3.3.1 Formulation of Panel

Due to the advantages of flexibility and productivity over other methods applied in extracting coal around the open-cut highwall, the underground panel in transition area is constructed based on concept of conventional punch longwall mining operation and the longwall panel was set up as the following procedure: Entries were
Table 3.1 Mechanical properties of rock mass and coal used in this analyses.

<table>
<thead>
<tr>
<th></th>
<th>In Weak Condition</th>
<th>In Strong Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rock mass</td>
<td>Coal</td>
</tr>
<tr>
<td>Density (kg/m$^3$)</td>
<td>1,950</td>
<td>1,430</td>
</tr>
<tr>
<td>UCS (MPa)</td>
<td>11.36</td>
<td>5.0</td>
</tr>
<tr>
<td>Bulk Modulus (MPa)</td>
<td>6.67 x 10$^3$</td>
<td>3.79 x 10$^2$</td>
</tr>
<tr>
<td>Shear modulus (MPa)</td>
<td>4.0 x 10$^4$</td>
<td>1.95 x 10$^2$</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Cohesion (MPa)</td>
<td>1.75</td>
<td>0.5</td>
</tr>
<tr>
<td>Friction angle (°)</td>
<td>25</td>
<td>22.3</td>
</tr>
</tbody>
</table>

drivaged across the horizontal plane of the coal seam along the roof. Considering typical longwall mining method, three-entry system was adopted in the analyses. The entries were connected by crosscuts, and chain pillars were formed between the entries. The dimensions of panel and pillars are initially taken based on design of a successful punch longwall mining operation in Australia. The panel width was initially taken as 300 m; the entries and crosscuts were set as 6 m in width and 3 m in height; and the pillars between the entries were designed as 30 m wide and 40 m
long. The short length of panel was firstly considered and it was taken as 300 m. The width of boundary pillar, which is measured horizontally from the toe of the slope to final face stop line of longwall, is varied depending on the response of ground/slope. The example and details of longwall panel modeled in the analyses are illustrated in the Figure 3.3. Three-dimensional analysis under symmetric condition was considered and half side from the center of the panel was analyzed.

### 3.3.2 Modeling Gob

In numerical analyses, it is well-known that modelling gob and its compaction process is a difficult task. Various researchers proposed different approaches based on sound theories on gob compaction, their experimental, analytical and numerical results (Salamon, 1990; Trueman, 1990; Xie, 1999). However, since the measurement of deformations and stresses in the gob is difficult due to the inaccessibility, there is still no standard method for modeling gob. In this study, the approach proposed by Xie et al. (1999) is employed and the following equation is used for estimating elastic modulus of gob.

\[
E = 15 + 175(1-e^{-12.5t})
\]  \hspace{1cm} (3.6)

where,
E = modulus of elasticity of gob materials (MPa)
t = time (s)

The gob is modeled as aggregate of fractured rocks and the Poisson’s ratio value of 0.3 is assumed in the analyses. The height of caving zone was calculated by the following relationship suggested by the Yavuz (2004).

\[
H_c = \frac{100h}{(c_1h+c_2)}
\]  \hspace{1cm} (3.7)

where,
\(H_c\) = caving height above top of the extracted horizon (m)
h = extraction thickness (m)
c_1, c_2 = empirically derived values depends on type of lithology
The $c_1$ and $c_2$ values for different lithologies are presented in Table 3.2 (Peng, 1984, Bai, 1995). The example of installation of gob in the simulations is illustrated in the Figure 3.4.

Table 3.2 Coefficients for various stratum lithologies. (Peng, 1984 & Bai, 1995)

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Compressive Strength (MPa)</th>
<th>$c_1$</th>
<th>$c_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong and hard</td>
<td>&gt;40</td>
<td>2.1</td>
<td>16</td>
</tr>
<tr>
<td>Medium strong</td>
<td>20-40</td>
<td>4.7</td>
<td>19</td>
</tr>
<tr>
<td>Soft and weak</td>
<td>&lt;20</td>
<td>6.2</td>
<td>32</td>
</tr>
</tbody>
</table>

Figure 3.4 Installation of gob during longwall mining process
3.4 Results and Discussions

3.4.1 Application of Conventional Longwall Mining Method and Design of Panels and Pillars in the Transition Area

Firstly, application of conventional longwall mining and response of ground and slope under strong and weak geological conditions were investigated. In the longwall mining practices, the minimum cover depth is generally planned as about 61 m in order to minimize potential for chimney caving to the surface (U.S. Bureau of Land Management, 2013). Therefore, in the analyses, longwall panels are developed under more than 60 m cover depth and the minimum boundary pillar left between the toe of the open-cut highwall and the end of longwall panel was initially taken as 100 m. According to the Equation (3.7) and Table (3.2), the height of the gob above the roof horizon for longwall mining method with 3 m mining height in strong geological condition was calculated as 13.45 m whereas 5.93 m for weak geological condition.

The contours of vertical displacement after extracting the longwall panel from 200 m, 300 m and 400 m deep pit slopes under strong and weak geological conditions are shown in Figures 3.5 (a)-(c) and 3.6 (a)-(c), respectively. Small displacements about 2.5-3 cm in maximum can be found at the slopes above the center of underground mine in all pit depths in strong condition. On the other hand, in weak conditions, it is found that the displacements at the slopes above the center of underground mine are about 5-5.5 cm in 200 m deep pit, and 6-6.5 cm in 300 m and 400 m deep pit, and areas of displaced zones along the slopes are larger with increasing pit depth. However, as the slope displacement less than 20 cm is acceptable for slope stability in most cases, it can be said the overall conditions of the slopes are in stable in all the pit depths in both weak and strong geological conditions.

The results of failure states in different pit depths under strong and weak geological conditions are shown in Figures 3.7 (a)-(c) and 3.8 (a)-(c). In the figure showing failure state, the terms in legend “none” indicates no-failure zone, “shear-n” and “tension-n” indicate yield in shear and tension now, “shear-p” and “tension-p” indicate elastic state in current, but yield in shear and tension past, respectively. It is found that the slope as well as boundary pillar are in very stable in all the pit depths in strong condition. In weak condition, boundary pillar is found in stable conditions in 200 m and 300 m depth, but pillar failure is occurred in the 400 m depth.
Figure 3.5 Contours of displacement after extracting longwall panel in strong geological condition (a) 200 m depth (b) 300 m depth and (c) 400 m depth (boundary pillar width = 100 m, panel width = 300 m)
Figure 3.6 Contours of displacement after extracting longwall panel in weak geological condition (a) 200 m depth (b) 300 m depth and (c) 400 m depth (boundary pillar width = 100 m, panel width = 300 m)
Figure 3.7 Failure states after extracting longwall panel in strong geological condition (a) 200 m depth (b) 300 m depth and (c) 400 m depth (boundary pillar width = 100 m, panel width = 300 m)
Figure 3.8 Failure states after extracting longwall panel in weak geological condition
(a) 200 m depth (b) 300 m depth and (c) 400 m depth
(boundary pillar width = 100 m, panel width = 300 m)
Figure 3.9 shows the results of failure states and contours of vertical displacement when the boundary pillars are increased into 150 m in the 400 m deep pit. It is found that the displacements at the slopes are decreased into 5.5-6 cm in compared with 100 m boundary pillar width and the impact of coal extraction on the slope becomes to be small. The failure zone at the boundary pillar also becomes to be small and the pillar is in stable condition.

According to the results discussed above, it is found that very small subsidence at the slopes and the boundary pillars as well as the slopes are stable in all the pit depths.
in strong geological condition. On the other hand, it is observed that the amount of subsidence at the slopes in the weak conditions is about two times of that in strong geological conditions. However, the subsidence about 5-6.5 cm is acceptable for slope stability. Therefore, it can be said that the conventional longwall mining method with panel width of 300 m is also applicable at the transition area in weak geological condition by using large boundary pillar.

3.4.2 Application of Multi-slice Longwall/Shortwall Top Coal Caving Method and Design of Panels and Pillars for Thick Coal Seam

In this section, the design of panels and pillars in transition area from surface to underground mine for thick seam under weak and strong geological condition are discussed. Due to the advantages of highest efficiency and productivity among the methods available for thick seam, longwall/shortwall top coal caving method is primarily considered in this study. In longwall top caving practices, although the method allows for about 10 m thick seam in one pass and up to 90% recovery of additional coal, coal recovery is less than expected in practical situation due to coal seam and strata conditions, about 60% of coal can be recovered in practical situation. Operational issues also limit top coal recovery and can often account for a greater percentage of the reduce recovery than geological conditions alone. In this study,

![Figure 3.10 Geometry, mesh and group of zone of the model (200 m depth)](image)

Figure 3.10 Geometry, mesh and group of zone of the model (200 m depth)
therefore, two slice system is considered for the 10 m thick coal seam, where the first slice is cut conventionally and next slice is extracted by top coal caving method. Basically, the height of mining for conventional cut for the first slice was considered as 3 m and next slice is set as 7 m, where coal thickness 3 m is cut along the mine floor and top coal 4 m in thickness is recovered. The scheme of multi-slice top coal caving mining method performed in the analyses is illustrated in Figure 3.11. The

Figure 3.11 Scheme of multi-slicing performed in the analyses
The panels and pillars were initially designed based on the results obtained from the application of conventional longwall mining under weak and strong geological condition presented in the previous section. Since it was found that the panel width of 300 m is also applicable in all pit depths (200 m, 300 m and 400 m) in both strong and weak geological conditions, the panel width of 300 m was initially taken for both geological conditions and ground behavior were investigated. Based on the results from conventional longwall mining practices presented in the previous section, the boundary pillar width of 100 m is initially taken for all the pit depths under strong geological condition, whereas the pillar width of 100 m for 200 m and 300 m deep pit, and the pillar width of 150 m for 400 m deep pit in weak geological conditions, respectively.

Figures 3.13-3.14 show the failure states and the contours of displacement after
extracting the longwall panel in first slice under strong geological conditions through the 200 m deep pit slope. It is found small displacement about 2.5 cm in maximum at the slope after first slice extraction with conventional cut and it is increased into 3.5-4.5 cm after second slice extraction by top coal caving method. However, this small displacement will not disturb on slope stability and it is within the acceptable limit. The slopes as well as boundary pillars are also in stable conditions after the second slice extraction.

Figure 3.13 Failure states and Contours of displacement after extracting first slice under strong geotechnical conditions.
(boundary pillar width = 100 m, pit depth = 200 m)
Figure 3.14 Failure states and Contours of displacement after extracting second slice under strong geotechnical conditions.
(boundary pillar width = 100 m, pit depth = 200 m)

Figures 3.15-3.16 show the failure states and the contours of displacement after extracting the panels in first and second slices under strong geological conditions through the 300 m and 400 m deep pit slopes, respectively. It is found that the slopes as well as boundary pillars are in stable conditions in all the pit depths. The small displacement at the slopes about 3.5-4.5 cm in maximum is also observed. Therefore, it can be said that the panel width of 300 m is also applicable if multi-slice longwall top coal caving mining method is applied and the boundary pillar width of 100 m is also appropriate in all the mining depths under strong geotechnical conditions.
Figure 3.15 Failure states and Contours of displacement after extracting first and second slices under strong geotechnical conditions.
(boundary pillar width = 100 m, pit depth = 300 m)
Figure 3.16 Failure states and Contours of displacement after extracting first and second slices under strong geotechnical conditions.
(boundary pillar width = 100 m, pit depth = 400 m)

Figures 3.17-3.18 show failure states and contours of displacement after extracting the longwall panels in the first and second slices under weak geological conditions from the 200 m deep pit slope. After extracting the first slice, it is found small displacement (about 4-4.5 cm in maximum at the slope). Failure at the mine roof is small and slope and boundary are in stable conditions. After extracting the second slice by longwall top coal caving method, however, the displacements at the
slope are significantly increased into 15-16 cm and large failures are occurred along the slopes and boundary pillars are failed.

Figure 3.17 Failure states and contours of displacement after extracting the first slice under weak geological condition
(boundary pillar width = 100 m, pit depth = 200 m)
Figure 3.18 Failure states and contours of displacement after extracting the second slice under weak geological condition (boundary pillar width = 100 m, pit depth = 200 m)

Figures 3.19-3.20 show failure states and contours of displacement after extracting the longwall panels in the first and second slices under weak geological conditions from the 300 m and 400 m deep pit slopes, respectively. It is also found that large failures are occurred along the slopes and boundary pillars are failed in all the depths. Large subsidence about 15-16 cm are observed at the slopes. Obviously, slope failures, large subsidence, overall slope instability problems and strata control issues in the underground workings can be expected in all the depths of 200 m, 300 m and 400 m. In these situations, since the large failures are occurred around the
panel, even though the problems of subsidence and failures at the slopes and boundary pillars might be reduced by increasing the pillar width, strata control problems will still be expected in the underground workings. Therefore, it can be said that the panel width of 300 m is not appropriate for thick seam under weak geological conditions.

Figure 3.19 Failure states and contours of displacement after extracting the first slice and second slices under weak geological conditions.
(boundary pillar width = 100 m, pit depth = 300 m)
Then, the smaller panel widths are designed and ground behavior is investigated. The panel width is decreased into 100 m and 3 panels are designed as shown in the Figure 3.21 and symmetric analysis is also performed. The inter-panel pillars are also designed as 30 m wide (60 m in total) and 40 m long. The boundary pillars are also designed as 100 m for 200 m and 300 m pit depths whereas 150 m for 400 m pit depths.

Figure 3.22 shows failure states and contours of induced displacement after
extracting first and second slices from 200 m deep pit slope. It is found that the failure zones at the mine roof are decreased significantly compared with 300 m panel width (Figure 3.18). The displacement at the slope is observed 6.5-7 cm in small area and about 5 cm in most part of the slope and therefore it is acceptable for overall slope stability. The boundary pillar is in stable condition. Therefore, it can be said that the boundary pillar width of 100 m, barrier pillar width of 60 m (in total) and panel width of 100 m is appropriate. However, the height of failure zones at the mine roof is still large, the roof control issues at the underground workings might still be expected.

Figures 3.23 and 3.24 show the failure states and contours of displacement when the multi-slice longwall is developed from the 300 m and 400 m deep pit slopes, respectively. It is found from these figures that small failures at the slopes and the slopes are stable. The vertical displacements at the slopes are also observed about 6.5-7 cm and thus it is acceptable for maintaining slope stability. However, large failures are still occurred at the boundary pillars in both the pit depths. In this situation, although the slope is currently in stable condition, since the pillar is failed,
if the condition at the toe of the slope is worsen, the whole slope stability would be occurred.

Figure 3.22 Failure states and contours of displacement after extracting the first slice and second slice under weak geological conditions. (boundary pillar width = 100 m, pit depth = 200 m)
Figure 3.23 Failure states and contours of displacement after extracting the first slice and second slice under weak geological conditions.
(boundary pillar width = 100 m, pit depth = 300 m)
Consequently, the widths of boundary pillars are increased into 150 m and 200 m in 300 m deep pit and the ground behavior is investigated. Figures 3.25 and 3.26 show failure states and contours of displacement in 300 m deep pit slope when the boundary is 150 m and 200 m, respectively. When the boundary pillar is 150 m, it is found that the failures at the boundary pillar are still observed. The failures at the boundary pillar are occurred when the width of boundary pillar is 200 m and slope is also in stable condition (see Figure 3.26). Therefore, it can be said that the width of boundary pillar for 300 m deep pit should be 200 m.
Figure 3.25 Failure states and contours of displacement after extracting the first slice and second slice under weak geological conditions.

(boundary pillar width = 150 m, pit depth = 300 m)
Figure 3.26 Failure states and contours of displacement after extracting the first and second slices under weak geological conditions. (boundary pillar width = 200 m, pit depth = 300 m)

Figure 3.27 shows failure states and contours of displacement in 400 m deep pit slope when the width of boundary pillar is increased into 200 m. It is found that the boundary pillar is still failed. Therefore, it was investigated the ground behavior by modeling with smaller panel width. The width of panel is decreased into 60 m and five panels are designed. For simplicity, two-entry system is applied for each panel and the total width of the inter-panel pillars are also designed as 60 m. The layout of panel is illustrated in the Figure 3.28.
Figure 3.27 Failure states and contours of displacement after extracting the first and second slices under weak geological conditions.  
(boundary pillar width = 200 m, pit depth = 400 m)

Figure 3.29 shows failure states and contours of displacement after extracting first and second slices from 400 m deep pit slope. It is found that the failure zones at the mine roof becomes to be small and displacements around the slope are decreased significantly. The displacement at the slope is decreased into 4.5-5 cm and at the mine roof is decreased into about 7 cm and thus it is acceptable. However, boundary pillar is still failed.
Subsequently, the panel widths are kept the same and the widths of inter-panel pillars were increased from 60 m to 100 m and the ground behavior is investigated. Figure 3.30 shows failure states and contours of displacement when the inter-panel pillar widths are increased into 100 m. It is found that the displacements at the slopes are decreased from 4.5-5 cm into 3.5-4 cm. In addition, a few failures are found at the boundary pillar. According to the results, therefore, it can be said that the boundary pillar width of 200 m, panel width of 60 m and barrier pillar width of 100 m is appropriate in transition area when thick coal seam are mined from 400 m deep pit slope.
Figure 3.29 Failure states and contours of displacement after extracting the first and second slices under weak geological conditions. (boundary pillar width = 200 m, pit depth = 400 m)
Figure 3.30 Failure states and contours of displacement after extracting the first and second slices under weak geological conditions. (boundary pillar width = 200 m, pit depth = 400 m)

3.4.3 Application of Multi-slice Longwall/Shortwall Top Coal Caving in conjunction with Stowing Method in Thick-seam under Weak Geological Condition

According to the results discussed above, it is found that multi-slice top coal caving method can also be applicable around the transition area from surface to underground mine by a proper panel and pillar design. However, since the large
amount of coal have to be left in the pillars, coal recovery will be decreased. Therefore, application of multi-slice longwall/shortwall top coal caving in conjunction with stowing method is also investigated and discussed for the thick seam under weak geological conditions in this chapter.

Figure 3.31 Layout of panels modeled in the analyses.

(panel width = 100 m, inter-panel pillar width= 60 m in total)

In the analyses, firstly the panel widths are initially designed as 100 m as shown in Figure 3.31 and boundary pillar widths are taken as 100 m for 200 m and 300 m deep pit, whereas 150 m for 400 m deep pit. The performance of stowing is investigated in two ways. The first one is slice-by-slice stowing, where stowing material is injected into the gob area when after all the panels at the first slice are extracted (see Figure 3.32). After that, the second slice is started along the mine floor and extraction is conducted by top coal caving method and stowing is installed after all panels at the second slice are extracted. The second one is panel-by-panel stowing where stowing material is injected immediately into the gob area after each panel is extracted. The procedure of panel-by-panel stowing is illustrated in the Figure 3.33. Since, the required strength of the stowing materials varies depends on the strata and
mining conditions: such as cover depth, rock type and properties, mining method, etc., here the properties of slurry stowing material, which is the compound ratio of cement, flyash, and water is 1:2:1, is firstly taken and the performance of stowing was investigated. The mechanical properties of this stowing material used in the analyses are: density 1,000 kg/m$^3$; Poisson’s ratio 0.23; Young’s modulus 1,000 MPa; tensile strength 0.5 MPa, cohesion 0.5 MPa, friction angle 26°, respectively.

At first, the performance of stowing is investigated in the 200 m deep pit. Figure 3.34 shows failure states and contours of displacement after extracting first and second slices with multi-slice longwall top coal caving using slice-by-slice stowing. It is found that failure zone around the mine roof becomes to be small dramatically and the displacement is decreased from 6.5-7 cm into 4-5 cm compared with
Figure 3.34 Failure states and contours of displacement after extracting the first and second slices with slice-by-slice stowing. (boundary pillar width = 100 m, pit depth = 200 m)

Figure 3.35 shows failure states and contours of displacement after extracting first and second slices with panel-by-panel stowing. It is found that the displacement is smaller than that in slice-by-slice stowing. The maximum displacement at the slope is about 2.5-3 cm, and thus it is obvious that panel-by-panel stowing is more effective to reduce subsidence. Since the subsidence at the slope is very small, the subsequent effect of subsidence at the slope such as failure, crack or sliding of slope will not be expected. In addition, since the failure at
Figure 3.35 Failure states and contours of displacement after extracting the first and second slices with panel-by-panel stowing
(boundary pillar width = 100 m, pit depth = 200 m)

the mine roof is smaller, it will also have better working environs in the underground workings. According to the results, therefore, panel-by-panel stowing is conducted in the subsequent analyses.

Figure 3.36 shows failure states and contours of displacement after extracting first and second slices with multi-slice longwall top coal caving using panel-by-panel stowing from 300 m deep pit slope. It is also observed that the maximum
displacement at the slope about 2.5-3 cm. The boundary pillar is also in stable and thus it can be said that the pillar width of 100 m is also enough for 300 m deep pit if stowing is applied.

Figure 3.36 Failure states and contours of displacement after extracting the first and second slices with panel-by-panel stowing (boundary pillar width = 100 m, pit depth = 300 m)

However, a boundary pillar failure is still observed in the 400 m deep pit although the displacement at the slope is small and about 3-3.5 cm after stowing (see Figure 3.37). Figure 3.38 shows the results when the boundary pillar width is
increased into 200 m in 400 m deep slope. No failures are found in the boundary pillar and thus it can be said the boundary pillar width should be larger than 200 m in the 400 m deep.

Figure 3.37 Failure states and contours of displacement after extracting the first and second slices with panel-by-panel stowing
(boundary pillar width = 150 m, pit depth = 400 m)
Figure 3.38 Failure states and contours of displacement after extracting the first and second slices with panel-by-panel stowing
(boundary pillar width = 200 m, pit depth = 400 m)

From the above discussions, it can be concluded that the stowing is effective method for prevent the failure of pillars and around the mine roof control and for control the displacement at the slope. It is also found that immediate panel-by-panel stowing is more effective in comparison with slice-by-slice stowing. In addition, stowing is also effective to increase the coal recovery. In comparison with previous results without stowing, the boundary pillar width 200 m need to be left in order to be in stable and to have safe operation in 300 m deep pit. If stowing is applied, the
boundary pillar width of 100 m is enough although the size of panel and inter-panel pillar sizes are the same. In 400 m deep pit, 4 pillars with 100 m in width (total 400 m in width) have to be left between 5 panels in order to avoid the failures at the pillar. Therefore, in the case of 400 m deep pit, the ratio of the width of panel to inter-panel pillar is approximately 0.75:1 when without stowing. However, if stowing is applied, the ratio of the width of panel to inter-panel pillar is approximately 2.5:1 when stowing is applied. In addition, since longer extraction length can be set, the productivity will also be higher.

3.5 Summary

The applicability of conventional longwall method in the transition area from surface mine to underground mine under weak geological conditions, the applicability of multi-slice longwall/shortwall top coal caving method for thick coal seams under different pit depths/geological conditions, and appropriate design of boundary pillars, inter-panel pillars and panels are investigated and discussed in this chapter. According to the results, it is found that conventional longwall mining method can also be applicable in the transition area from open pits to underground mine under weak geological conditions. However, the deeper the pit depth is, the more stress concentrates around the toe of the slope obviously in weak geological conditions. Therefore, when the 300 m width of coal panel is extracted by conventional longwall method with 3 m height in the pit depth of 400 m, the 100 m wide of boundary pillar is enough in strong geological conditions, but the 150 m or wider boundary pillar has to be left under weak geological conditions.

In mining of thick seam by multi-slice longwall/shortwall top coal caving method under strong geological condition, slope stability problems are not be expected even the panel width of 300 m is applied. The boundary pillar width of 100 m is enough in all the mining depths conditions. In weak geological condition, however, it is found that a large impact of coal seam extraction on the slope and geotechnical problems including slope failures, boundary pillar failures, large ground subsidence, and large failures at the mine roof can be expected when the panel width 300 m is applied. Therefore, it is suggested that the width of the panel becomes to be small and the panel width of 100 m is appropriate in 200 m and 300 m deep pit. The boundary pillar width of 100 m is suitable for 200 m deep pit, but 200 m for the 300 m deep pit.
In the 400 m deep pit, however, the boundary pillar width of 200 m, panel width of 60 m and inter-panel pillar width of 100 m is required in order to maintain the stability of the slope and mining operation in the transition area from open pit to underground mine.

In order to increase the coal recovery and improvement of stability of slope, the application of multi-slice longwall/shortwall top coal caving in conjunction with stowing for weak and thick seam is proposed and discussed in this chapter. It is found that stowing is quite effective to prevent the pillar failure and to control the stability and subsidence at the slope. As the results, the coal recovery can be improved. No operational problems due to subsidence and strata control issues at the underground mine are expected in all the depths when stowing is applied. It is found that the panel width of 100 m can be designed in all the pit depths and boundary pillar widths of 100 m is appropriate at the transition area for 200 m and 300 m deep pits. But in the case of 400 m deep pit, 200 m wide boundary pillar should be left.

3.6 References


4.1 Introduction

In the previous chapter, the criteria for the applicability and the design of the single to multi-slice extraction method at the transition area from surface to underground mine, appropriate mining method and design for panels, boundary pillars, and inter-panel pillars in the transition area were studied. According to the results, it is found that multi-slice top coal caving method can also be applicable around the transition area from surface to underground mine by a proper panel and pillar design. However, since the large amount of coal have to be left in the pillars, coal recovery will be decreased. Stowing had proved to be quite effective in reducing the subsidence at the slope, as well as reducing the failures around the panel and pillars and maximizing the coal recovery and the immediate panel-by-panel stowing is more effective in comparison to slice-by-slice stowing. Based on the mining method and design criteria for thick coal seam under weak geological conditions obtained in the previous chapter, applicability of multi-slice top coal caving method and design for the transition area at the Mae Moh Mine is investigated and discussed in this chapter.

For numerical analysis, geometry of model is constructed based on the final pit design of Mae Moh Mine and boundary and initial conditions are also set up the same as presented in the previous chapter. The details about the formulation of numerical model including the set up underground structures and slope, and the discussion on the applicability of multi-slice top coal caving method and design for the transition area in Mae Moh Mine are presented in this chapter.

4.2 Formulation of the Numerical Model

Figure 4.1 shows the geometry of model, mesh and group of zones included in the numerical model. The model is composed of 20 m thick two coal seams, named as K seam and Q seam, with the interburden of 30 m and overburden of 500 m in
Figure 4.1 Geometry, mesh and group of zones of the model

Figure 4.2 Bench design of Mae Moh pit
thickness. The distance between the toe and crest of the slope is 1,500 m, which was set up the same as the distance in final pit design, and the overall slope angle is about 18 degrees in the model. The total dimension of the model is 600 m in width, 2,200 m in length and 670 m in height, respectively. The height and width of the each bench are set as 10 m, the bench slope angle is 45 degrees and the berm width is 20 m in the model (see Figure 4.2). For simplicity, multi thin layers were not considered and the overburden, interburden and underburden are modeled as homogeneous claystone layers. The extraction of upper coal seam (K seam) is considered in this analyses. Smaller meshes were set up at the seam and the region closed to the extraction area in order to obtain more precise stress, induced displacement, and failure distribution around the extraction area. The bottom of the model is restricted in the vertical direction, whereas the sides of the model are restrained perpendicular to each side. Mohr Coulomb elasto-plastic constitutive model is employed in the analyses. The mechanical properties of the materials used in the numerical analyses are presented in Table 4.1.

**Table 4.1 Mechanical properties of the materials used in the numerical analyses.**

<table>
<thead>
<tr>
<th></th>
<th>Claystone</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>1,950</td>
<td>1,430</td>
</tr>
<tr>
<td>UCS (MPa)</td>
<td>11.4</td>
<td>3.02</td>
</tr>
<tr>
<td>Bulk Modulus (MPa)</td>
<td>$6.67 \times 10^3$</td>
<td>$1.67 \times 10^2$</td>
</tr>
<tr>
<td>Shear modulus (MPa)</td>
<td>$4.0 \times 10^4$</td>
<td>35.7</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Cohesion (MPa)</td>
<td>1.75</td>
<td>0.16</td>
</tr>
<tr>
<td>Friction angle (°)</td>
<td>25</td>
<td>22.3</td>
</tr>
</tbody>
</table>

**4.3 Slope Stability Analysis**

The slope stability of the final pit of Mae Moh Mine is analyzed through the factor of safety calculation firstly. The factor of safety of the slope was also calculated by strength reduction method using FLAC3D. Two-dimensional problem under plan-strain condition is also considered and 1-block model is employed for the factor of safety calculation. Figure 4.3 presents the results of shear strain rate contours developed at the last non-equilibrium state of the shear reduction routine. The maximum shear strain is found at the toe of the slope and at the coal seam ‘Q’,
and the circular failure surface is observed to propagate from the pit floor through the ‘Q’ coal seam. The minimum factor of safety of the slope is calculated as 2.45 and therefore, it can be said that the overall condition of the final highwall in Mae Moh Mine is in stable before the development of underground coal mine.

Figure 4.3 Contours of shear strain and factor of safety around the final pit slope at Mae Moh Mine.

4.4 Investigation of the Applicability of Multi-slice Top Coal Caving Method and Design for the Transition Area from Open Pit to Underground Mine

4.4.1 Extraction of Coal Seam without Stowing

Firstly, applicability of multi-slice longwall/shortwall top coal caving method at the transition area without stowing are investigated. According to the results presented in the previous chapter, it has been found that the boundary pillar width of 200 m, panel width of 60 m and inter-panel pillar width of 100 m is appropriate when thick coal seams are extracted by multi-slice longwall methods without stowing from 400 m deep pit slopes. Based on these results, the panels and pillars are initially designed and ground behavior is investigated. However, according to the results in the previous chapter, it was found that the subsidence at the slope increases with increasing pit depth. Therefore, in the analyses for Mae Moh Mine, the panel width become to be small as 50 m and the behavior of ground and slope is investigated. Figure 4.4 shows the example of the panel layout performed in the analyses. The entries are set as 5 m in width. The pillars between the entries are designed to be
100 m wide and 40 m long, and the width of the boundary pillars are initially also taken as 200 m in the analyses based on the design criteria for thick seam under weak geological condition from the 400 m deep pit. The first slice is also done along the mine roof with 3 m mining height. Gob is modeled as the same method presented in the section 3.3.2. The scheme of development of first slice is illustrated in Figure 4.5.

Figure 4.4 Panel layout modeled in the analyses.
(panel width=50 m, inter-panel pillar width=100 m, boundary pillar width=200 m)

Figure 4.5 Extraction of first slice performed in the analyses.
Figure 4.6 shows the results of failure states and contours of induced displacement after extracting all panels (five panels) at the first slice. It is found that the small vertical displacement at the slope (about 2.5-3 cm in maximum) and no failures occurs at the slope. Boundary pillar is in stable condition. Failures at the mine roof are also small and operational problems at the underground workings are not expected in this situation. From the results, it can be said that the design of boundary pillar, inter-panel pillars and panel are appropriate in the single slice operation.

![Figure 4.6 Failure states and contours of displacement after extracting five panels at the first slice. (boundary pillar width = 200 m)]
As the coal seams at Mae Moh mine are very weak and coal seams are extra thick, obvious impact on slope stability would be expected if large caving are occurred. Considering this situation, thickness of top coal in the second slice is initially taken as 3 m and mining height is also taken as 3 m in the second slice as shown in Figure 4.7. The width and length of panels and pillars are also designed as the same sizes as in the first slice and five panels are also designed in the second slice.

![Figure 4.7](image)

Figure 4.7: Extraction of second slice by top coal caving method performed in the analyses.

Figure 4.8 shows the results of failure states and contours of induced displacement after extracting five panels at the second slice. It is found that the displacement at the slope is increased into 5.5-6 cm and large failures are occurred at the slope above the rib side of the extracted panels. Small failures are also occurred at the boundary pillar around the toe of the slope.

![Figure 4.8](image)
Consequently, the boundary pillar width is increased into 300 m and the response of model is investigated. Figures 4.9 and 4.10 show the results of failure states and contours of induced displacement after extracting five panels at the first slice and second slice respectively. It is found that the displacement at the slope is slightly decreased about 2-2.5cm in maximum and no failures occurred at the slope after the first slice extraction is completed. However, after the second slice extraction, displacement at the slope is also significantly increased and slope failures are occurred at the rib side of the underground mine due to the subsidence above the underground mine. In this situation, the occurrence of large slope failures can be expected. Therefore, it can be said that the multi-slice top coal caving method without stowing would not be feasible around the transition area of Mae Moh Mine even the second slicing.
Figure 4.9 Failure states and contours of displacement after extracting five panels at the first slice. (boundary pillar width = 300 m).
Figure 4.10 Failure states and contours of displacement after extracting five panels at the second slice. (boundary pillar width = 300 m).

4.4.2 Extraction of Coal Seam with Stowing

Consequently, it was investigated application of multi-slice longwall top coal caving in conjunction with stowing method. Considering available by-products, which can be used as stowing material, from Mae Moh power plant, flyash and gypsum are used as stowing material in this study. Based on the laboratory test results of the compounding ratios of flyash, gypsum and water 2:1:1, the mechanical
properties of stowing material listed in the Table 4.2 are used for Mae Moh Mine.

### Table 4.2 Mechanical properties of stowing material used in the numerical analyses.

<table>
<thead>
<tr>
<th>Stowing material (water:flyash: gypsum= 2:1:1)</th>
<th>Density (kg/m³)</th>
<th>Bulk Modulus (MPa)</th>
<th>Shear Modulus (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Cohesion (MPa)</th>
<th>Frictional Angle (Deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2,000</td>
<td>$11.1 \times 10^2$</td>
<td>$8.33 \times 10^2$</td>
<td>0.8</td>
<td>0.8</td>
<td>26</td>
</tr>
</tbody>
</table>

Based on the application of longwall top coal caving in conjunction with stowing and design criteria for thick seams from 400 m deep pit under weak geological condition presented in previous chapter, the widths of panels are initially designed as 100 m in the analyses. The layout of panels is illustrated in Figure 4.11. The inter-panel pillars are also taken as 30 m wide and 40 m long and boundary pillar width is taken 200 m as well. Three panels are initially designed and response of slope/ground was investigated. Symmetric analysis is also performed in the analyses. The proposed method for Mae Moh mine presented in the section (2.3) is applied in the analyses. The first slice is also extracted with conventional cut with 3 m mining height and stowing is injected into the gob immediately after each panel is extracted. After

![Figure 4.11 Panel layout modeled in the analyses.](image)

(panel width=100 m, inter-panel pillar width= 60 m in total)
extracting the panels and stowing at the first slice, second slice is extracted with applying top coal caving method by also leaving top coal thickness of 3 m and cutting height of 3 m. The width and length of panels and pillars are also designed as the same sizes as in the first slice. The scheme of multi-slice top coal caving method applied in the analyses is illustrated in the Figure 4.12.

Figure 4.12 Scheme of multi-slice top coal caving with stowing method performed in the analyses.

Figures 4.13 and 4.14 show the results of failure states and contours of induced displacement after extracting and stowing three panels at the first slice and second slice, respectively. The small displacement of about 2-2.5 cm is observed at the slope and about 4 cm at the mine roof after first slice extraction. The boundary pillar as well as the slope are found in stable conditions. After extracting and stowing three panels at the second slice, the displacement is increased into about 5 cm at the slope and the occurrence of slope failures can still be expected after extracting the second slice.
Figure 4.13 Failure states and contours of displacement after extracting three panels with stowing at the first slice.

(panel width=100m, inter-panel pillar width = 60 m)
Therefore, smaller panels are designed and the response of ground is investigated. The panel width is decreased into 50 m and five panels are initially designed. The inter-panel pillars are also set as 50 m and stowing was done panel by panel. The layout of the panels is illustrated in the Figure 4.15. Figures 4.16 and 4.17 show the results of failure states and contours of induced displacement after the panels at the first slice and second slice are extracted and stowed. After the panels at the first slice are extracted and stowed, the displacement at the slope is found smaller
(about 1.5-2 cm) than the previous results with 100 m panel width (see Figure 4.13). A small failures are also observed at the boundary pillar. After the second slice is extracted and stowed, it is found that the displacement as well as failures around the slope become to be small in comparison with previous results (see Figure 4.14). Although failures zone in the boundary pillar and around the panels become to be small, the occurrences of slope failures is still expected.

Figure 4.15 Panel layout modeled in the analyses (panel width = 50 m, inter-panel pillar width =50 m)
Figure 4.16 Failure states and contours of displacement after extracting five panels with stowing at the first slice (panel width=50 m, inter-panel pillar width =50 m)
Figure 4.17 Failure states and contours of displacement after extracting five panels at the second slice (panel width=50 m, inter-panel pillar width =50 m).

Therefore, it was also investigated the response of ground and performance of stowing by modeling with smaller panel. The width of each panel is taken as 30 m and the inter-panel pillars are also taken as 30 m and nine panels are initially designed. The panel layout is illustrated in the Figure 4.18.

Figure 4.18 Panel layout modeled in the analyses. (panel width = 30 m, inter-panel pillar width =30 m)
Figure 4.19 shows the results of failure states and contours of induced displacement when the panels at the first slice are extracted and stowed. The displacement at the slope is found much smaller (about 1-1.5 cm) and no failures are also found at the boundary pillar.

Figure 4.19 Failure states and contours of displacement after extracting nine panels at the first slice.

(panel width = 30 m, inter-panel pillar width = 30 m, boundary pillar width = 200 m)

Figure 4.20 shows the results of failure states and contours of induced displacement after the panels at the second slice are extracted and stowed. The
displacement at the slope is found about 4 cm and only a small failure is found at the slope and boundary pillar. Therefore, it can be concluded that the shortwall mining method with immediate stowing panel-by-panel is more appropriate in the transition area in the situation of Mae Moh Mine and the suitable sizes of each element are panel width of 30 m, inter-panel pillar width of 30 m and boundary pillar width of 200 m. According to the results, therefore, 35% of the coal recovery (excluding boundary pillar) can be obtained around the transition area.

Figure 4.20 Failure states and contours of displacement after extracting nine panels at the second slice. (panel width = 30 m, inter-panel pillar width = 30 m, boundary pillar width=200 m)
4.5 Summary

According to the results obtained from the numerical simulations, the overall condition of the final highwall is expected to be in stable condition in Mae Moh Mine. However, many geotechnical problems were expected due to the slope failures and subsidence when multi-slice top caving without stowing system was applied. Only single slice can be mined without stowing system in the transition area. It is found that mining in conjunction with stowing is quite effective to control surface subsidence. However, in the situation of Mae Moh Mine, since the coal seams are too weak and final highwall are very huge, application of multi-slice top coal caving method with large panel width might not be feasible at the transition area from open pit to underground mine even the stowing is applied. Large slope failures are occurred even the subsidence about 5 cm is observed at the slope. According to the results, it can be found that multi-slice top coal caving method with the short panel width of 30 m and immediate stowing after panel extraction is more appropriate at the transition area from open pit to underground mine to control the slope failures as well as subsidence in the situation of Mae Moh Mine. It was also found that the boundary pillar width of 200 m is appropriate and two-slice extraction can safely be extracted at the transition area by applying multi-slice top coal caving in conjunction with stowing method and 35% of coal recovery can be obtained in the transition area.

4.6 References

EGAT reports and presentation slides, Geotechnical Engineering Department, Mae Moh Mine Planning & Administration Division, 2011.


CHAPTER 5
APPLICABLE UNDERGROUND MINING METHODS FOR EXTRA-THICK COAL SEAM AT THE DEEPER SITE FROM OPEN-CUT HIGHWALL IN MAE MOH MINE

5.1 Introduction

In the previous chapter, it was discussed and proposed the applicable mining method and design criteria of pillars and panels in the transition area from open pit to underground mine. According to results, it is found that two-slice extraction can safely be done in the transition area using stowing method in Mae Moh Mine. In the situation of Mae Moh Mine, as there exist considerable coal reserves in the deeper site from highwall as shown in the Figure 5.1., it is also important to develop applicable mining method for those considerable deposits. Therefore, it is proposed applicable mining methods for the weak extra-thick coal seams at the deeper site from highwall in Mae Moh Mine and discussed the applicability of the systems in this chapter.

Figure 5.1 The distribution of K and Q coal seams at the final highwall.

5.2 Proposed Underground Mining Methods for Extra-thick Coal Seams at the Deeper Site from Highwall

As the Mae Moh power plant mainly relies the coal supplies from Mae Moh mine, it is important to get coal from the seams as much as possible. However, when maximizing coal extraction, it is also required to consider obvious subsidence and its subsequent effect of extra-thick seam mining. If large subsidence occurs, it is
Possible for water resources and other surface features to be disturbed, causing flooding of the mine and the extra expense of water pumping. Especially sensitive is the fossil national park, water management facilities, reservoirs, and surface facilities that exist around the underground mining area; and because of that more attention has to be paid when maximizing coal recovery at the deeper site from final highwall. Moreover, as the two coal seams are very thick and the mechanical properties of rocks in this mine are very poor, it can be expected that the underground mining operation will have obvious impacts on the ground and surface. Considering the situations, the following two mining systems are proposed for deeper site from final highwall of Mae Moh Mine:

(1) Multi-slice Longwall Top Coal Caving with Stowing Method

Since it is sensitive for subsidence in the situation of Mae Moh Mine, immediate installation of roof support in the gob area behind the longwall face is recommended to support and control roof sagging and caving in the gob. After supporting, the stowing operation in the gob area will be started. After three to six months, the stowing gob is consolidated and the next slicing starts by top coal caving method (see Figure 5.2).

![Figure 5.2 Multi-slice longwall top coal caving with stowing system.](image)
(2) Multi-slice Bord-and-Pillar with Stowing Method

The multi-slice bord-and-pillar mining system with proper size of pillars is quite effective in surface control, such as subsidence and caving in. However, the coal recovery is decreased with increasing mining depth because larger pillars have to be left in order to maintain pillar stability and sufficient strata control. In addition, the pillar may cause difficulties by deteriorating, cracking, catching fire, and so on. Since the mechanical properties of coal seams are very weak and the coal seams are extra thick in Mae Moh Mine, it is expected that considerable amount of lignite will be left as pillars if conventional multi-slice bord-and-pillar method is applied. Therefore, it seems that the application of conventional multi-slice bord-and-pillar system has limited potential in the situation of Mae Moh Mine.

Therefore, the following method is proposed for the given conditions: Continuous miners start mining the first slice coal in descending order (top to bottom), leaving proper size pillars in each slice. Mining is repeated until the first slice is fully developed. After each panel reaches the prescribed length, stowing is done using a hydraulic system. Three to six months later, the filling entries are consolidated, and then the remaining coal pillars in the first slice coal are extracted by the same mining system. However, appropriate pillar size must be very thoroughly investigated. After completing the first slice mining, the second slice is developed and mined underneath the first slice using the same mining and stowing systems.

5.3 Numerical Analysis

In Mae Moh mine, the coal seams are widely distributed in the deeper site from highwall in various depths as shown in Figure 5.1. Most parts of the seams are deposited around 400-500 m depth from the surface. In this study, therefore, the thickness of overburden is taken as 400 m and thickness of K seam is taken as 20 m, while the thickness of interburden between the seams and Q-seam is taken as 25 m, respectively. The upper coal seam, K is only focused in this study and a smaller mesh size was selected at the seam. The dimension of the model is 220 m wide, 220 m long and 470 m high, respectively. The geometry, mesh and group of zones of the model are presented in the Figure 5.3. The mechanical properties of coal and claystone used in this numerical analysis are presented in Table 5.1.
Table 5.1. Mechanical properties of material used in numerical analyses.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Bulk Modulus (MPa)</th>
<th>Shear Modulus (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Cohesion (MPa)</th>
<th>Frictional Angle (Deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1,430</td>
<td>$12.50 \times 10^2$</td>
<td>$5.77 \times 10^2$</td>
<td>0.3</td>
<td>0.8</td>
<td>22.3</td>
</tr>
<tr>
<td>Claystone</td>
<td>1,950</td>
<td>$14.00 \times 10^2$</td>
<td>$8.40 \times 10^2$</td>
<td>1.0</td>
<td>1.2</td>
<td>33.5</td>
</tr>
</tbody>
</table>

Figure 5.3 Geometry, mesh and group of zones of the numerical model

5.4 Results and Discussion

5.4.1 Application of Multi-slice Longwall Top Coal Caving with Stowing Method

As the geological and geotechnical conditions at Mae Moh mine are poor and weak, the width of the panel was considered as 100 m and mining height is considered as 3 m. The first slice is developed along the mine roof (the top of K-seam). Installation of cribs is immediately followed after face advance. Spacing of the cribs is set as 5 m in rows and 4 m in columns each other. Cribs were modelled as
elastic constitutive material and typical young’s modulus value of 8,600 MPa is adopted. Stowing is followed right after the installing cribs. The same stowing material properties used in the previous chapter are used in the analyses. The scheme of mining and stowing is illustrated in the Figure 5.4.

![Figure 5.4 Scheme of longwall mining with temporary support and stowing.](image)

Figures 5.5(a) and (b) show the results of vertical displacement and distribution of failure zones along the center of panel after extracting first slice with temporary roof support and stowing system. It is found the failures and closure at the mine roof are controlled effectively. The displacement at the mine roof is found 7-8 cm and small active failure zones (shear-n) at the mine roof and floor are observed. After extracting and stowing the first slice, next slice extractions were conducted by applying longwall top coal caving method with leaving top coal 3 m thickness and cutting height of 3 m is also applied in each slice. Stowing is followed after each face advance as the same manner as in the first slice. Figures 5.6-5.8 show the distribution of failure zones developed during the excavation process in the second slice, third slice and fourth slice respectively. It could be seen from those figures that active failures zones (shear-n) are observed above the longwall face during the extraction and this indicate that top coal is caved enough during the face extraction. No large active failures are observed at the roof of each slice and thus strata control problems are not expected in each slice of extraction.
Figure 5.5 (a) Vertical displacement and (b) distribution of failure zones along the center of panel after extracting and stowing at the first slice.
Figure 5.6  Distribution of failure zones along the center of panels (a) after 96 m face advance at the second slice (b) after completing the extraction of second slice.
Figure 5.7  Distribution of failure zones along the center of panels (a) after 96 m face advance at the third slice (b) after completing the extraction of third slice
Figure 5.8 Distribution of failure zones along the center of panel after extracting the “K” coal seam.

Figure 5.9 Subsidence at the surface after extracting the “K” coal seam.

Figure 5.9 shows the vertical displacement at the surface after completing the extraction of fourth slice. Only the vertical displacement about 8.25 cm in maximum is observed at the surface after completing the extraction of the 20 m thick extra-thick coal seam. According to the results of series of numerical analysis, therefore, it can be said that this extra-thick coal seam in this mine can be extracted without any large impacts on the surface facilities by means of multi-slice longwall
top coal caving with temporary supports and stowing system.

5.4.2 Application of Multi-slice Bord-and-Pillar with Stowing Method

At first, the ground responses are investigated by applying conventional bord-and-pillar method. The width and length of the panel is also taken as 100 m and 150 m. The dimension of each gallery is taken as 6 m in width and 3 m in height, respectively. Descending order of extraction is also considered and, the first slice is modeled along the roof.

Figures 5.10 and 5.11 show the failure states at different sizes of pillars after the first slice is developed along the mine roof. The pillar width and length is 12 m in Figure 5.10 and 18 m in Figure 5.11, respectively. According to the results, it could be seen that all the pillars in Figure 5.10 are failed (shear-n, tension-n) whereas pillars seemed to be in stable in Figure 5.11 although partial failures are occurred. Therefore, the pillars size is considered starting from the 18 m in width and length in the analyses.

Figure 5.10 Failure states at pillars after developing first slice along the roof.
(pillar width x length =12 m x 12 m)
Figure 5.11 Failure states at pillars after developing first slice along the roof.
(pillar width x length =18m x 18m)

Figures 5.12 and 5.13 show the conditions of pillars, after the second slice is developed in superimposed and non-superimposed pattern, where the coal parting 3 m is left between the slices. According to these results, it is found that pillars are completely failed in the superimposed pattern of extraction whereas the pillars at the first slice and roof coal partings are failed although partial failures are occurred at the pillars in the second slice in the staggered pattern. Therefore, it is expected that pillar instability and roof control problems occur in both patterns of developments.
Figure 5.12 Failure states after developing the second slice in superimposed pattern (a) view along the central part of the panel and (b) pillars in the second slice.
Figure 5.13 Failure states after developing the second slice in staggered pattern 
(a) view along the central part of the panel and (b) pillars in the second slice.

Consequently, the performance of the proposed bord-and-pillar method with 
stowing is employed and response of ground and pillars are investigated. The 
sequence of cutting and stowing performed in the analyses is illustrated in the 
Figure 5.14. According to the pillar design approach presented above (Figure 5.11), it

Figure 5.14 Sequence of excavation and stowing performed in the analyses.
is found pillar width of 18 m is appropriate in the given ground condition. Therefore, the width of pillars are also taken as 18 m in this study. At first, pairs of entries with 6 m in width and 3 m in height are driven across the mine roof by leaving 18 m wide pillars between them. After that these entries are stowed and then another pairs of entries are driven next to the stowed entries. The mining and stowing procedures are repeated in the same manner until the whole panel was extracted.

Figure 5.15 shows sequence of excavation and stowing in the extraction of panel at the first slice and results of failure states in each mining sequence. According to the results of failure states shown in Figures 5.15(a), (b), (c) and (d), it is found that the pillars maintained their stability until the whole panel is extracted. Second slice was conducted beneath the first slice. Figures 5.16(a) and (b) show contours of

Figure 5.15 Failure states along with the sequences of mining and stowing at the first slice (a) after 1st cut, (b) after stowing the 1st cut, (c) after 2nd cut and (d) after extracting and stowing the whole panel.
vertical displacement and failure state after cutting pairs of entries at the second slice. According to the results, it is found a very few active failures zones (shear-n, tension-n) at the roof and small displacement about 2-4 cm in maximum around the openings and therefore, the problems in roof control and pillars failure will not be expected.

Figure 5.16 (a) Contours of vertical displacement and (b) failure states after 1st cut at the second slice.
Mining and stowing were repeated in the second slice in the same manner as the first slice. The next slice extractions are also done slice by slice sequentially in descending order and no large roof control and pillars instability problems are expected during the extractions. Figures 5.17(a) and (b) show contours of vertical displacement at the surface and failure state after extracting the whole K seam. It can be seen that the subsidence at the surface is only 9.75 cm and failures around the extracted seam are very small even after the whole seam (20 m thick) is extracted.
Therefore, it can be concluded that the proposed mining methods mentioned above are applicable and effective method for mining extra-thick seam in terms of ground control, mine safety and coal recovery.

5.5 Summary

In this chapter, it is investigated and discussed applicability of multi-slice longwall top coal caving method and multi-slice bord-and-pillar method in conjunction with stowing for the weak extra thick coal seam at the deeper site from the final highwall in Mae Moh Mine. According to the results of a series of numerical analysis, it is found that multi-slice longwall top coal caving with temporary supports and stowing system as well as multi-slice bord-and-pillar mining with the alternative method of cutting and stowing system can be employed for the weak extra-thick coal seam and they are effective methods to diminish ground disturbance and subsidence, to improve mine safety and to maximize coal recovery. While estimating mining costs and effectiveness in these two methods, application of longwall method with stowing will be more expensive due to the initial capital cost for longwall equipment. However, much easier operation, higher productivity will be achieved. On the other hand, application of bord-and-pillar method with stowing would be less expensive and more flexible. However, productivity will be lower and operation will be more complicated. It is found that bord-and-pillar method with alternative method of cutting and stowing can also provide the same percentage of coal recovery as longwall with stowing method and full thickness of coal in the panel can be extracted. However, the selection of mining method must be made depends on geological conditions of the mine.

5.6 References


EGAT reports and presentation slides, Geotechnical Engineering Department, Mae Moh Mine Planning & Administration Division, 2012.


With increasing industrialization worldwide, the demand of coal is increasing year by year. To meet the demand for coal in Asian countries, and the rest of the world, the development of new coal mines from open-cut highwall is being planned in several mines in Southeast Asian countries including Thailand, Indonesia, etc. in In Southeast Asian countries, geological conditions at the most of the coal mines are weak and some coal mines have thick coal seams. However, the development of mining method and design for mines under weak geological conditions and for thick seams are not well developed so far. Therefore, to develop mining method and design for thick seams under weak geological condition are great important for Southeast Asian countries to meet the demand of coal in local as well as for the rest of the world. From these backgrounds, a mining system and design for development of underground coal mines from open-cut highwall, especially for weak and thick coal seams have been proposed in this study.

In this study, the Mae Moh Mine, where the final pit is designed to be very deep (500 m), coal seams are extra-thick and geotechnical properties of coal seams is very weak, was chosen as a representative mine in order to study mining system and design for development of underground from open-cut highwall for weak-thick coal seams.

Firstly, appropriate mining method and criteria for applicability and design of the single to multi-slice extraction method at the transition area from surface to underground mines for different pit depths and thickness of coal seams under strong and weak geological conditions were studied. To investigate the response of ground/slope under the different situations, numerical models with different pit depths and different thickness of coal seams and different material properties were constructed employing FLAC3D finite different codes. Due to the many advantages, in terms of safety and productivity, over other underground mining methods, the application of longwall/shortwall top coal caving method is especially considered for thick coal seams. In order to investigate whether conventional longwall mining method can be applicable in the transition area in weak geological conditions, the thickness of coal seam was considered as 3 m firstly and the applicability of conventional longwall method around the transition area in weak geological
conditions was investigated. According to the results, it is found that conventional longwall mining method can also be applicable at the transition area from open pits to underground mine under weak geological conditions. However, the results revealed that the deeper the pit depth, the more stress concentration around the toe of the slope and it is more significant in weak geological conditions. It is found that the panel width of 300 m and boundary pillar width of 100 m is appropriate in all the pit depths of 200 m, 300 m and 400 m in strong geological conditions. But, it is required the boundary pillar width of 150 m in 400m deep pit, although the pillar width of 100 m is appropriate in 200 m and 300 m deep pits in weak geological conditions.

In mining of thick seams by multi-slice longwall/shortwall top coal caving method under strong geological condition, slope stability problems are not be expected even the panel width of 300 m is applied. Boundary pillar width of 100 m is enough in all the mining depths conditions. In weak geological condition, however, it is found that large impact to the slope and many problems including slope failures, boundary pillar failures, large ground subsidence, and large failures at the mine roof is occurred when the panel width 300 m is applied. But, it is found that the panel width of 100 m is appropriate in 200 m and 300 m deep pit. The boundary pillar width of 100m is suitable for 200m deep pit, but 200m for the 300m deep pit. In the 400 m deep pit, however, the boundary pillar width of 200 m, panel width of 60 m and barrier pillar width of 100 m is required in order to have stability at the transition area from open pit to underground mine. In order to increase the coal recovery and improvement of stability of slope, application of the longwall/shortwall top coal caving in conjunction with stowing method is proposed and discussed. Stowing had proved to be quite effective in reducing the subsidence at the slope, as well as reducing the failures around the panel and pillars and maximizing the coal recovery. In addition, the immediate panel-by-panel stowing is more effective in comparison to slice-by-slice stowing. No obvious operational problems due to subsidence and strata control at the underground mine are expected in any of the depths when stowing is applied. A panel width of 100 m can be designed for all the pit depths and the boundary pillar widths for 300 m and 400 m deep pits are 100 m and 200 m, respectively.

After that, slope stability of final highwall, applicability of multi-slice longwall/shortwall top coal caving method and appropriate design of pillars and panels around the transition area for Mae Moh pit were investigated based on the
design criteria from weak and thick coal seams. It was found that the overall condition of the final highwall is expected to be in stable condition and slope design is appropriate until the final pit limit. However, many geotechnical problems were expected due to the slope failures and subsidence when multi-slice top caving without stowing system was applied. Only single slice can be mined without stowing system in the transition area. Mining in conjunction with stowing is quite effective to control surface subsidence. However, in the Mae Moh Mine, since the coal seams are too weak and the open-cut highwall are very large, multi-slice longwall top coal caving would not be feasible at the transition area from the open pit to the underground mine, even if the stowing is applied. Large slope failures occurred even though a subsidence of about 5 cm is observed at the slope. According to the results, it is found that a shortwall with the length of 30 m and immediate stowing after panel extraction is more appropriate at the transition area from the open pit to the underground mine in order to control the slope failures, as well as subsidence, in the Mae Moh Mine. It was also found that a boundary pillar width of 200 m is appropriate, and the two-slice extraction can safely be applied at the transition area in conjunction with stowing method.

At last, alternative methods of mining in conjunction with stowing for the weak and extra-thick coal seams at the deeper site from the highwall at the Mae Moh Mine is proposed. The application of the multi-slice longwall top coal caving method and multi-slice bord-and-pillar method in conjunction with stowing, for mining the weak and extra-thick coal seams at the deeper sites of open-cut highwall are proposed and discussed. According to the results of a series of numerical analyses, it was found that multi-slice longwall top coal caving with temporary supports and stowing system, as well as multi-slice bord-and-pillar mining with an alternative method for the cutting and stowing system, can be employed for the weak and extra-thick coal seams. These are effective methods for diminishing ground disturbance and subsidence in order to improve mine safety and to maximize coal recovery. Since there are many by-products from coal fired power plant that can be useful as stowing material, if these by-products and the waste rocks are used as stowing materials, it can be less initial capital cost, can minimize the amount of the waste to be managed on surface and can also be useful for supporting underground mine. It is found that both methods offered same percentage of coal recovery and full thickness of coal seams can be extracted in the extraction area by using multi-slice top coal caving or multi-slice bord-and-pillar in conjunction with stowing methods. Therefore, the
selection of method can be made depends on the geological conditions, equipment availability and economy of mine and both are effective and useful methods for weak and thick coal seams.