การออกแบบการทำเหมืองวิธีสว่านเจาะผนังเหมือง: กรณีศึกษาที่เหมืองถ่านหินแม่ทาน ประเทศไทย

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DESIGN OF AUGER HIGHWALL MINING:

A CASE STUDY AT MAE TAN COAL MINE, THAILAND

Miss Sophea Boeut

A Thesis Submitted in Partial Fulfillment of the Requirements

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โซเฟีย เบือท : การออกแบบการทำเหมืองวิธีสว่านเจาะผนังเหมือง: กรณีศึกษาที่เหมืองถ่านหินแม่ทาน ประเทศไทย (DESIGN OF AUGER HIGHWALL MINING: A CASE STUDY AT MAE TAN COAL MINE, THAILAND) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: พิพัฒน์ เหล่าวัฒนบัณฑิต, 88 หน้า.

เหมืองถ่านหินส่วนใหญ่ที่ใช้วิธีทำเหมืองผิวดินจะหยุดเมื่อถึงขอบเขตบ่อเหมืองสุดท้าย อย่างไรก็ตามในบางพื้นที่พบว่ายังมีถ่านหินปริมาณมากเหลืออยู่ในผนังเหมืองที่สามารถขุดออกมาด้วยวิธีการทำเหมืองวิธีอื่น การทำเหมืองวิธีเจาะผนังเหมืองเป็นวิธีการทำเหมืองกึ่งผิวดิน-ใต้ดินที่เริ่มพัฒนาในช่วงปี 1940 ในประเทศสหรัฐอเมริกา วิธีการนี้เหมาะสมที่จะขุดถ่านหินที่เหลือดังกล่าวในทางเทคนิค วิธีการเจาะผนังเหมืองสามารถแบ่งออกเป็น 2 แบบ คือ แบบต่อเนื่องและแบบเจาะซึ่งจะให้รูสี่เหลี่ยมและวงกลมตามลำดับ รถเจาะผนังเหมืองถูกนำมาใช้เจาะถ่านหินเพื่อยืดอายุเหมืองหรืออัตราส่วนขุด

ในการศึกษานี้ วิธีการศึกษาเชิงประจักษ์บางวิธีถูกนำมาเปรียบเทียบกับวิธีโมเดลเชิงตัวเลข 3 มิติ ด้วยโปรแกรม FLAC3D เพื่อออกแบบระบบเสาค้ำยันในการเจาะผนังเหมืองกรณีพิเศษเฉพาะสำหรับเหมืองถ่านหินแม่ทาน ความเค้นและความแข็งแรงของเสาค้ำยันถูกศึกษาโดยวิธีการทั้งสองกฎเกณฑ์หลายอย่างถูกกำหนดขึ้นมาเพื่อประเมินรูปแบบที่เหมาะสมสำหรับเหมืองถ่านหินนี้ ผลลัพธ์ของความเค้นจากการวิเคราะห์เชิงตัวเลขมีค่าใกล้เคียงกับทฤษฎีเงประจักษ์ ยิ่งกว่านั้นความแข็งแรงจากโมเดลเชิงตัวเลขยังมีค่าใกล้เคียงกับค่าเฉลี่ยของวธีการเชิงประจักษ์ ดังนั้นค่าเฉลี่ยของสมการเชิงประจักษ์ถูกแนะนำให้ใช้ได้สำหรับถ่านหินแม่ทาน ที่ปัจจัยความปลอดภัย 1.6 สำหรับเสาค้ำยันใย และ 1.0 สำหรับเสาค้ำยันผนังกั้น ผลลัพธ์ที่ได้แสดงให้เห็นว่าเมื่อการเจาะลึกขึ้นปริมาณถ่านหินจะเพิ่มขึ้นแต่เปอร์เซ็นต์การขุดลดลง ตามการออกแบบเสาค้ำยันสามแบบจะได้ปริมาณถ่านหินที่แตกต่างกัน ในที่สุดแล้วตามเสถียรภาพและผลผลิตถ่านหิน รูปแบบการขุดหลายชั้น ด้วยหัวเจาะเส้นผ่านศูนย์กลาง 1.5 เมตร เสาค้ำยันใย 1.5 เมตร และเสาค้ำยันนังกั้น 2.0 เมตรจะเป็นรูปแบบที่แนะนำสำหรับที่นี่ รูปแบบการขุดหลายชั้นนี้ประกอบด้วยการเจาะสองชั้นในถ่านหินชั้นล่างและการเจาะหนึ่งชั้นในถ่านหินชั้นบน การเจาะสองชั้นในถ่านหินชั้นล่างได้ถูกออกแบบให้ระยะห่างระหว่างแถวที่ 0.8 เมตรซึ่งเป็นรูปแบบที่มั่นคงที่สุด นอกจากนี้ความลึกของการเจาะที่ปลอดภัยสำหรับถ่านหินชั้นบนคือ 55 เมตร และ 60 เมตรสำหรับถ่านหินชั้นล่างจะเหมาะสมสำหรับเหมืองถ่านหินแม่ทาน

ภาควิชา วิศวกรรมเหมืองแร่และปิโตรเลียม ลายมือชื่อนิสิต ....

สาขาวิชา วิศวกรรมทรัพยากรธรณี ลายมือชื่อ อ.ที่ปรึกษาหลัก ....

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KEYWORDS: AUGER, BARRIER PILLAR, DOUBLE PASSES, EMPIRICAL ANALYSIS, HIGHWALL MINING SYSTEM, NUMERICAL ANALYSIS, MULTIPLE PASSES, SINGLE PASS, WEB PILLAR. / AUGER, BARRIER PILLAR, DOUBLE PASSES, EMPIRICAL ANALYSIS, HIGHWALL MINING SYSTEM, NUMERICAL ANALYSIS, MULTIPLE PASSES, SINGLE PASS, WEB PILLAR

SOPHEA BOEUT: DESIGN OF AUGER HIGHWALL MINING: A CASE STUDY AT MAE TAN COAL MINE, THAILAND. ADVISOR: PIPAT LAOWATTANABANDIT, Ph.D., 88 pp.

Most coal mines that adopted surface mining method have been stopped after reaching the ultimate pit limit. However, in some areas, there is still some significant amount of coal in the highwall that can be extracted using other mining methods. Highwall mining method, which is considered as the semi surface-underground mining operation, was originally developed in the early 1940s in the US. It is suitable to excavate the remaining coal. Technically, there are two types of highwall mining: continuous and auger highwall mining with the rectangular and circular opening respectively. The highwall miners are used to drill the residual to extend the mining life or recovery ratio.

In this study, few empirical approaches were compared to the 3D modeling of FLAC3D to design the pillar system in highwall mining special case to Mae Tan Coal Mine. The stress and strength of the pillars were investigated from both types of theories. Several criteria were proposed to estimate one optimum design for this coal mine. The result of stress from the numerical analysis provided almost the same as an empirical theory. Moreover, the strength from numerical modeling also similar to the average empirical strengths. Hence, the average result of empirical equations was suggested to use for Mae Tan coal. The result, at the safety factor of 1.6 for web pillar and 1.0 for barrier pillar, showed that the quantities of coal increased when the penetration length was made deeper, although the percent recovery of coal decreased. According to the pillar design of the three categories, the amount of mined coal was not the same. As the last observation on the stability and coal production, the multiple passes with the auger diameter of 1.5 m, web and barrier pillars of 1.5 m and 2.0 m were suggested. Furthermore, the multiple passes were the combination of double passes at the lower seam and single pass at the upper seam. The double passes at the lower seam were designed by keeping the vertical spacing between two holes of 0.8 m, which is the most stable case. In addition, the safe entry lengths of the upper and lower seam are 55 m and 60 m as the final recommendation for Mae Tan Coal Mine.

Department:	Mining and Petroleum Engineering	Student's Signature	....
Field of Study:	Georesources Engineering	Advisor's Signature	....
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CHAPTER 1

INTRODUCTION

1.1 General information

Besides the power plant consumption, coal is supplied to the cement plant, steel factories as the main fuel for combustion. In many countries, coal is considered as the important sources of energy, which is about 40 percent of electric power supply and the annual increasing rate of demand of coal is about 0.2 percent. As the numerally stated, coal, in Poland, is consumed about 94 percent, in South Africa approximately 92 percent. China consumes 77 percent of coal and Australia requires about 76 percent of coal [1].

In Thailand, from the recovery of economic crisis, the consumption of electricity is quite notably expanded with the annual demand rate increasing by 7.1 percent, 6.9 percent, and 6.5 percent between the years of 2004-2008, 2009-2013 and 2014-2015 respectively. The main sources of electricity in Thailand are from natural resources, fuel and lignite. Eighty percent of lignite is supplied to power generation while the other twenty percent shared to industrial sectors [2]. Vichakul [3] made his presentation in the Philippines in 2015, indicating that the consumption of lignite is about 6.5 percent from domestic lignite and 4.6 percent of coal is imported from foreign countries. In balancing the requirement of energy, and as stated in the Energy Policy and Planning Office in 2010, Thailand is trying to extract coal as much as it can in order to extend the reserve remaining in the old mining area, to promote the new mine licenses or international investment.

Relating to the continuous removing coal remaining from the old mining sites, the highwall mining system is considered as the second mining method for extending the mining life after surface mining. HM is more attractive from many countries after the original history from the US in last half of 1970s and it is commercially used in 1980s. Australia had announced the first application of highwall mining by BHP in 1989

[4] and also applied in New Zealand. Recently, this highwall mining system has been also applied in India. Somehow, Thailand is researching on highwall systems in order to extract coal in this country. The examples would be given to Mae Moh Coal Mine which has done its research on highwall system in 2013 [5] and now to Mae Tan Coal Mine.

1.2 Problem formulation

Most coal mines in Thailand are using surface mining methods which extract coal/lignite from the top to the bottom. Located in Lampang province, the northern part of Thailand, Mae Tan Coal Mine is using the open pit mining to mine coal for supplying to the cement plants as the main fuel of SCG group. It is impossible to mine 100% coal without any coal left behind the bench after the final pit reached. Highwall mining system, which is efficiently used in the US, Australia, and India now are favorable to extract the remaining coal in the final pits of surface mining where the extended pit cannot be accessed because of the slope stability, area limited boundary and regional geology. Mae Tan coal is not well horizontal reserve. It is considered as the semi surface-underground mining method to lengthen the production life of surface mining. Auger mining would provide the easiest and the most efficient way to Mae Tan Coal Mine. The cost would be less since the overburden has been already removed and haul roads has been already constructed. The concept is to use the auger miner with the head rotation into horizontal or declined coal layers creating circular holes. The dip angle of coal seam would be less than 15 degrees to apply this method. The problem in Thailand is about resquesting a new mining lenience. This reason makes the companies try to extract the existing coal reserves as much as possible

However, slope stability is still one of the problems of this mining system. The observation before, during and after mining should be carried out. The process is to excavate coal from the highwall by leaving some coal as the pillar supports, and the overburden soil subjects the load to pillars. Moreover, while rolling into the coal layers, the auger machine creates fracture surrounding the pillars. So these phenomena will reduce the strength of the pillar support. If the pillar supports are not strong enough, the collapse will occur. A suitable safety factor must be selected with the consistence with the percent recovery for the design.

1.3 Purposes of the research

In the description of the problem mentioned in section 1.2, two categories are mainly discussed.

- To extract the coal seam left in the final pits of an open pit by Auger Highwall Mining.
- To investigate the stability of the pillars and highwall system.

1.4 Scopes of work

As mentioning in the previous section, this research is worked principally on auger highwall mining and slope stability of the system after designing. To reach the analysis, many factors are included in the design. Those related factors are listed below:

- Recognize the geology of the study area: site investigation, identify the discontinuity from core drilling, stratigraphy of the research area.
- Investigate the application of Mark-Bieniawski (1999), Salamon Munro (1967) and UNSW (1996) empirical modeling on the augering system at Mae Tan Coal Mine in Thailand.
- Design the proper pillars with FLAC3D.
- Include the previous research concepts on Highwall mining combination to reach one approval of efficient auger highwall mining.

1.5 Research location

1.5.1 Background

The research is accomplished at Mae Tan Coal Mine which belongs to SCG group, in Lampang province, the northern part of Thailand. The coal is primarily mined to supply to the cement plant in Lampang province. Lampang is the third largest town in the northern Thailand, with the distance of 601 kilometers from north Bangkok and 101 kilometers from Chaing Mai [6]. General rank of coal ranges from lignite to bituminous in the Tertiary age [7]. The mine location is shown in Figure 1-1. The yellow star is Bangkok capital of Thailand, and the red point is research area in Lampang province.

Figure 1-1: Research location [8].

1.5.2 Regional Geology

The open pit mining is almost finished which means that the final pit is about to be reached. The contour lines of the final pit at Mae Tan is shown in Figure 1-2 with the light blue color. Moreover, the darker blue color is representing the final pits where the auger highwall mining will be applied. The total length of the remaining coal reserve is about 600 m and the distance from the slope face of the final pit to the highwall is 120 m long. Based on the data from Mae Tan mine, the remaining coal reserve is about one million tons. Then, the auger highwall mining is considered as the most appropriated mining technology for Mae Tan coal mine.

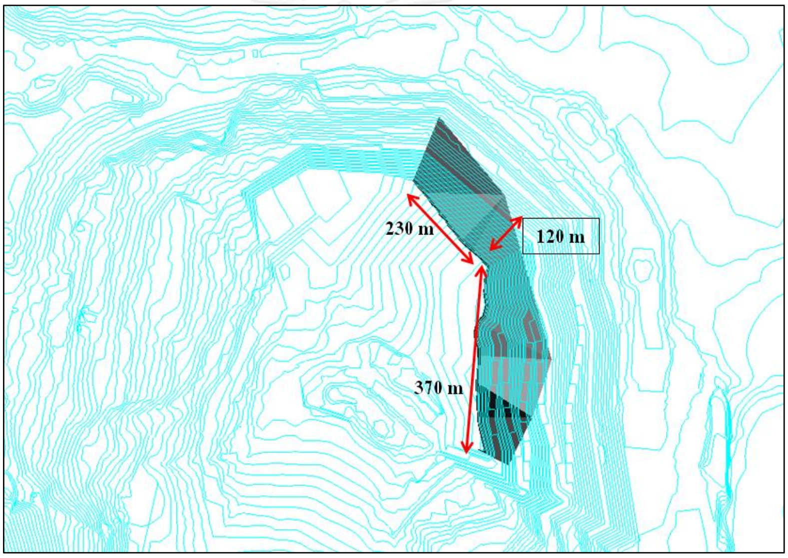


Figure 1-2: Final pit map of Mae Tan Coal Mine [9].

Observing on the stratigraphy of the area, there are five types of rock excluding coal such as top soil red clay, sandstone, shale, ball clay, carbonaceous shale and Rhyolitic tuff. The whole lithography of rock is provided in Figure 1-3. The elevation at the top is about 288-meter-high varied to about 120 meters high at the bottom. According to the lithography, sandstones are the thickest layer and then the top soil. Two coal layers, the upper one is about 2.5 meters thick and the second layer is about 4 meters thick.

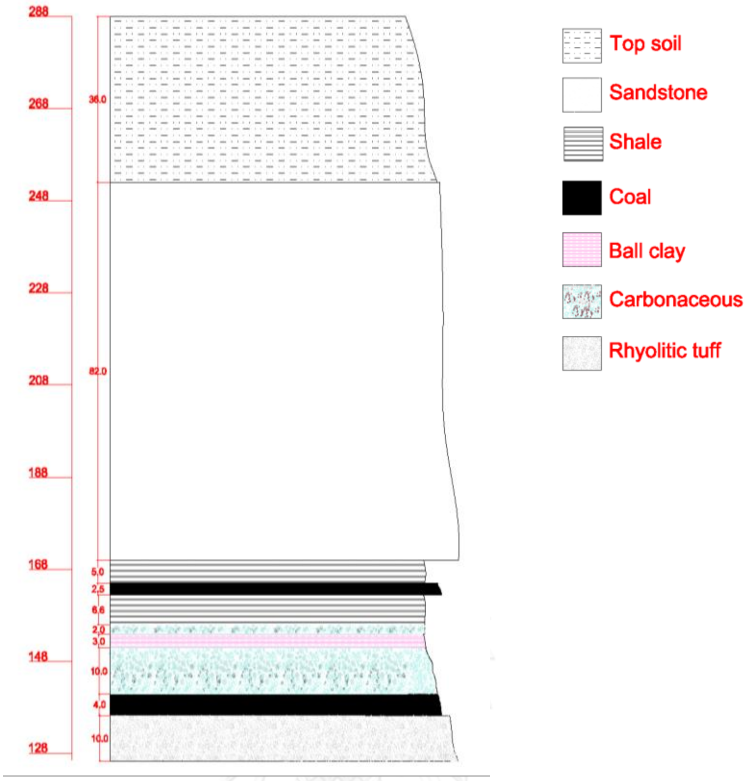


Figure 1-3: Stratigraphic column of Mae Tan Coal Mine.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Since coal is an indispensable resource, new researching methods to extract coal reserve as much as possible have been becoming more interesting. As the semi-underground and surface mining, Highwall Mining system is considered to be the most economic method to dig coal left in the final pit from the open pit, open cut mining, opencast mining, trench mining or contour mining in the opinion of the slope stability, mining boundary condition [5, 10] and the geology condition. The overburden is one of the most influencing factors in stability for Hignwall mining including the economic term of stripping ratio [11]. Technically, the general concept of Highwall Mining system is to drill the horizontal or inclined circular or rectangular holes into the coal seam in parallel; the coal seams which are left from the highwall of the existing surface mining. The main purpose is to recover the remaining coal reserve with keeping the pillars as the supports. These supports are between the dug holes to forbid the collapsing of the overburden [12].

The safety conservation in the design is the key point to protect the humanity and equipment. The slope stability record, the mine pillar arrangement design would be enthusiastic focused in this chapter. Moreover, chapter also covers several methods to analyze the pillar system, and further related assignment to the research such as the stratigraphy, the conceptual manual for software application and procedure.

2.2 Highwall mining system

The Highwall mining system in which most researchers believe that it could help to extend the mining life and give the additional coal quantity, the systems are partitioned into two main types, namely, the continuous miners and auger miners

(Figure 2-1). These two systems are operated in the different conditions of coal strata upon the geology, coal seam shape and length, and remaining reserve quantity. The extraction capacity of the continuous miner or add-car highwall mining is higher than AHM. The extraction capacity and the accessible drilling length ability of CHM is higher than AHM. However, the capital cost of AHM is lower than CHM.

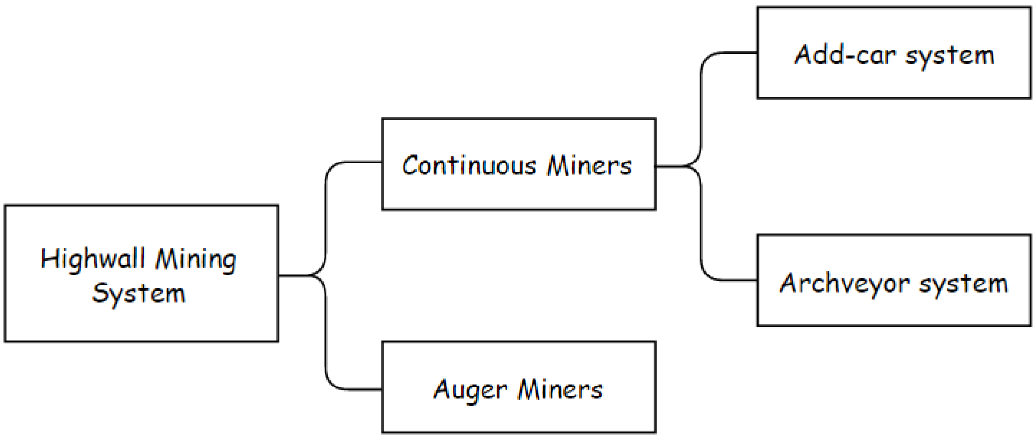


Figure 2-1: Classification of highwall mining system [13]

2.2.1 Continuous highwall mining

CHM is the application of continuous mining machine in which the rectangular opening is generated into the coal seams at the highwall and the conveyor systems carry out coal from the machine. The system is divided into Add-Car system and Archveyor system (Figure 2-2 and 2-3); the entry is now accessed to 350 meters long with the different diameters based on the continuous miners [5], and the mining capacity is about 1,000,000 tons per year [13, 14] as shown in Table 2-1, but the mining capacity can be increased until 1.5 million tons in case the seam is thick enough [15]. Add-car system cannot be applied in the thin-seam coal, it is mostly used in more than 0.9 meters thick [15]. Figure 2-2 shows the feature of the Add-care system and its working process. The latest highwall mining is Archveyor system which contains simple equipment like a continuous miner, a chain conveyor, and a load-out vehicle. The system works very facilely; it mines in a rectangular opening in the coal seam of that highwall, then the conveyor transports coal from miners to the load-out vehicle. The next step is to move coal from each hole to the surface for transporting (Figure 2-3) [16]. Kumar ,[15],mentioned in the website titled highwall mining, the Archveyor of Joy 12CM is capable cutting 3.8-meter coal seam of 1.8 to 4.9 meters thick. The total cost of this mining method is less as it is the second mining approach after the surface mining. The huge overburden thickness has already removed. Furthermore, it needs less working force, around 12 people for total 3 shifts according to Bucyrus SHS [15], and it is the same as Venkat, [17], who stated that the requirement of people per shift of work is 3 to 4 people. Anyhow, there are 60% to 70% of total coal can be recovered with the dip angle of fewer than 15 degrees [17]; between +5 degrees to -12 degrees [15]. Thus, it gives the brilliant challenge in conducting this method to excavate the left coal behind a highwall. Additionally, the remote control is a secure system for personal protection since it lets people work from a distance. People can command the system outside the miners which mean that people do not have to go underground and avoid themselves from the risk of rock or roof fall, dust, gas, flooding, irrespirable atmospheres; and very beneficial in working in the gassy seam condition [15, 18]. The continuous highwall mining is well equipped with advanced navigation technology, the combination of roof and floor passive gamma detector system, inclinometers, a ring laser gyroscope and a programmable logic control [19]. All the materials supplied in HWM and the movement system of HWM provides the high safety for the whole mining system that encourages this system becomes more popular and convenient method in the mining sector. The removing system of highwall mining lets the machine work at various locations. In the future, it is predicted to become the final method used for the coal extraction after the pit limited is reached.

Table 2-1: Estimation of auger and highwall mining production for 2003 [20]

Machine	Number of faces in operation	Productivity (Raw tons per year)	Production (raw tons)
Superior Highwall Miners	30	650,000	20,000,000
Add-car Highwall Miner	30	1,000,000	30,000,000
Augers	150	100,000	15,000,000
Total (raw tons)			65,000,000
Total (clean tons)			45,000,000

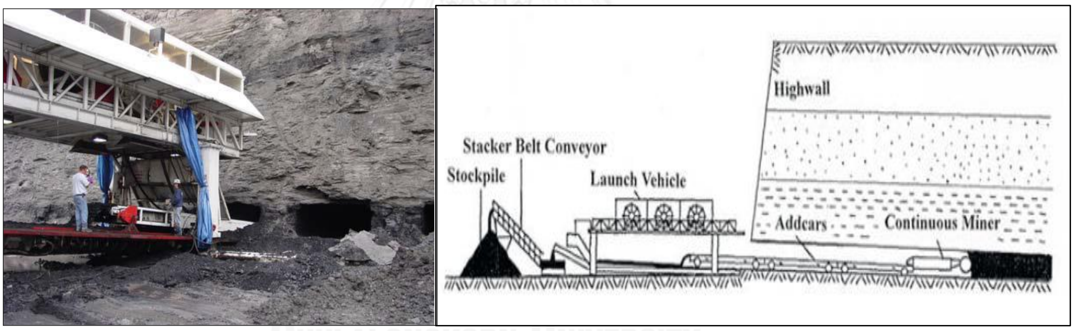


Figure 2-2: Add-car highwall mining system [5, 13]

Figure 2-3: Archveyor system (left) and Load-out vehicle (right), [16].

2.2.1.1 Continuous highwall mining stability

While coal production is very important, the safety of the whole operation is taken into account since there arises millions of expense in case problems occur. Highwall mining stability, studied by many researchers who have been trying very hard and carefully on the safety, is one of the main factors in deciding whether this method can be applied for coal extraction or not. In this point of view, the previous publications are reviewed to strain the basic concepts in designing for this new research. In this part of the research, the author tries to collect various numerical modeling mentioning specifically on the rectangular punching. Mark-Beiniawski empirical model is well-known in the US, Salamon Munro empirical model in South Africa and UNSW empirical model in Australia. The web and barrier pillars are the main supports for the highwall stability. Figure 2-4 is the schematic of continuous highwall mining system shows the coal seam, web and barrier pillars, and web cut.

Such parameters as the depth of overburden, the pillar widths, pillar height including pillar length penetrated into the coal seam are the framework for this study. In addition, the rock properties are very important for the stability evaluation about the structure strength. The stress and strength of web and barrier pillars are the most important for the safety estimation. Some empirical formulae for estimation the factor of safety of the continuous highwall mining will be shown later.

Figure 2-4: Continuous highwall mining geometry.

2.2.1.1.1 Web pillar design

Starting from the web pillar representation, the formula by Mark-Bieniawski for the rectangular web pillar is very popular and many researchers use it. The narrow rectangular web pillar equation is the target to use for the highwall mining. In addition, the literature is also involved two more empirical theories of Salamon Munro and UNSW in this research. These empirical equations are favorably applicable in the US, South Africa and Australia which are then shown in Table 2-2. The Strength of pillar tends to increase in strength relating to the ratio of width to height of the pillar increases [21]. The equation (1), (2) and 3 are expressed the pillar strength according to Mark-Bieniawski empirical theory [22], Salamon-Munro of South Africa [23] and UNSW of Australia [24]

Table 2-2: Pillar Strength Estimation

	Strength formulae	Original	
Mark-Bieniawski	$S_P = \sigma_C(0.64+0.54\frac{W}{h})$	USA (1999)	Eq. 1
Salamon Munro	$S_P = \sigma_C\frac{W^{0.46}}{h^{0.66}}$	South Africa (1967)	Eq. 2
UNSW	$S_P = \sigma_C\frac{W^{0.52}}{h^{0.84}}$	Australia (1996)	Eq. 3

Where: S_p : web or barrier pillar strength

σ_c : UCS of coal

W_p : web or barrier pillar width

h_p : Pillar height (or height of web/barrier pillars)

The mining height, h_p, is the vertical height related with all excavated holes both rectangular and circular holes. It can be greater or less than exact coal seams based on how big is the heading of the machine or a number of rows of holes as in the vertical direction. The next formula is submitted to the coal web pillar stress, σ_p.

$$\sigma_P = \sigma_v \left(\frac{W_p + W_E}{W_p} \right) \qquad \text{Eq.4}$$

$$\sigma_v = \gamma H \qquad \text{Eq.5}$$

Where σ_p : stress of web or barrier pillars

W_p : web pillar width

W_E : opening width

σ_v : vertical stress

The safety of factor *SF* can be calculated as:

$$SF_P = \frac{\text{Web pillar strength}}{\text{Web pillar stress}} = \frac{S_P}{\sigma_P} \qquad \text{Eq.6}$$

2.2.1.1.2 Barrier pillar design

The barrier pillar is designed following the same concept of the web pillar by replacing the web pillar width to the barrier pillar width in the equations in Table 2-2.

If the number of web pillars in a panel is (N), the panel width (W_{PN}) can be calculated as in Eq. 7.

$$W_{PN} = N(W_P + W_E) + W_E \qquad \text{Eq.7}$$

Where W_P and W_E are the web pillar and the opening widths. Ignoring stress carried by the web pillars, stress on barrier pillar can be calculated as in Eq. 8. Barrier pillar will always prevent the domino failing in case there is any web pillar failed and barrier pillar is considered as a necessary since lignite is very weak. So then the factor of safety can be calculated as in Eq.9.

$$\sigma_{BP} = \sigma_v \left(\frac{W_{PN} + W_{BP}}{W_{BP}} \right) \qquad \text{Eq.8}$$

$$SF_{BP} = \frac{\text{Barrier pillar strength}}{\text{Barrier pillar stress}} = \frac{S_{BP}}{\sigma_{BP}} \qquad \text{Eq.9}$$

Based on a data researched by MSHA on highwall ground control [20], the values of the safety factor of web pillar are not always the same. The safety of factor which is ranged from 1.3 to 1.6 is used 30 percent cases. If greater than 1.6 is used about 45 percent of cases. For Indian coalfields, the safety of factor is exceeding 2.0 which are used for the long-term stability [11]. The safety factor of barrier pillar can be as low as 1.0 since the stress carried out by web pillar is ignored.

2.2.2 Auger highwall mining system

Auger mining system, the second part of the highwall system, has practiced since the 1940s in the US. The auger machine can be drilled into the coal seam with a single or couple circular holes, which is about 200 meters long with the approximated production up to 60,000 tons (about 66,000 tons) per month. The latest capacity of augering machine, [14], is higher than the previous auger miner capacity, about 100,000 tons per year (Table 2-1). The accessible capacity of the auger miner is less than 15 degrees of coal seam dip angle. However, the new machine can be drilled into 23 degrees of coal seam dip angle in Australia and 16-23-degrees dip in Indonesia [25]. This convenience of Auger miners makes the companies choose either this system to finish the end-up coal left in the final pit of the highwall or there are no methods. The quantity of the recovered coal by the refined auger from the coal strata of a highwall is depending on the diameter of the auger miner, the vertical spacing between holes (septum), the barrier distance between each panel and the safe entry length into the seam of the auger miners. These factors control the production capacity which is the points in selecting this mining method or else. Along with the production, the design on diameters and spacing design should be considered. The Auger mining systems are divided into three phases: single, double and multiple phases. The single phase is confirmed to have only one row of hole (Figure 2-6). Secondary, the double phase is the technique of application two rows of auger holes, which has the lower first hole and the upper second holes (Figure 2-7). The final is multiple phases. The Multiple is the application of auger miner into different coal seams (Figure 2-8).

Auger miners consist of cutting head, auger flight, latching mechanism and auger fork. The working process of auger miner is very common. Firstly, the auger cutting head drives directly from the auger machine into the coal seam and the additional flights are added as the hole deepens. Once each flight is in place, a tractive effort is provided by hydraulic rams. Each auger flight is connected via a latch pin assembly that operates by remote control from the operator's air-conditioned cabin [5]. As the coal is extracted from the augering hole, a side conveyor advances the coal onto a stacker belt for stockpiling. The augering system runs through the wetting approach, as the hydraulic skids are equipped along this working procedure. The other point of view, the wetting system is very helpful for coal mining system to prevent various problems as coal dust, the self-combustion of coal, etc., (Figure 2-5).

Figure 2-5: Auger mining system [26].

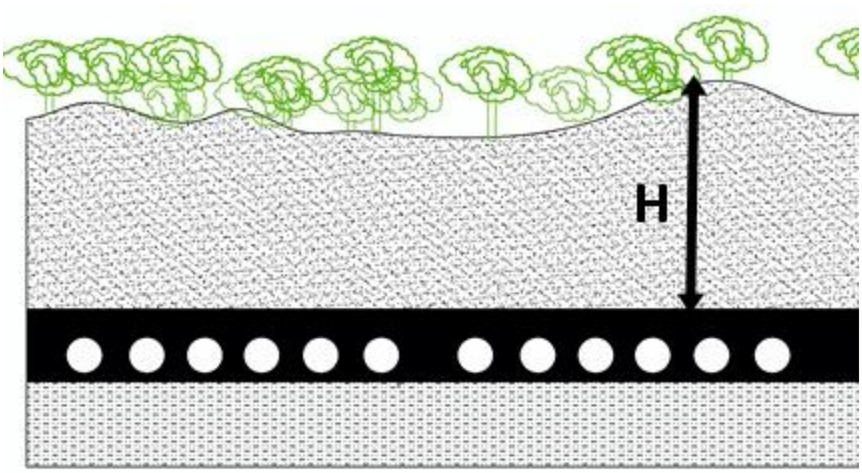


Figure 2-6: Single pass of the augering system [27].

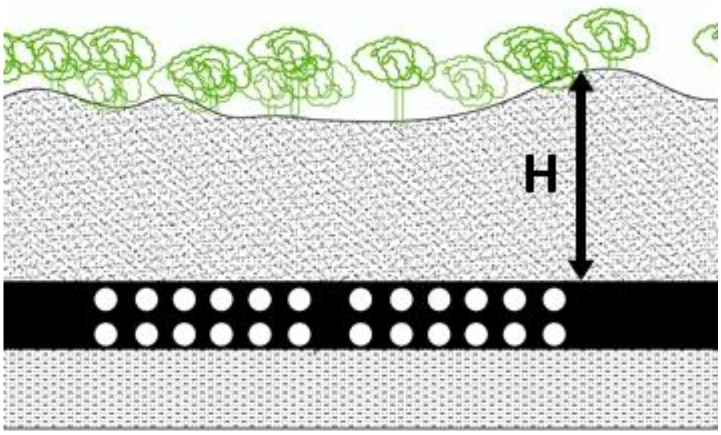


Figure 2-7: Double passes of the augering system [27].

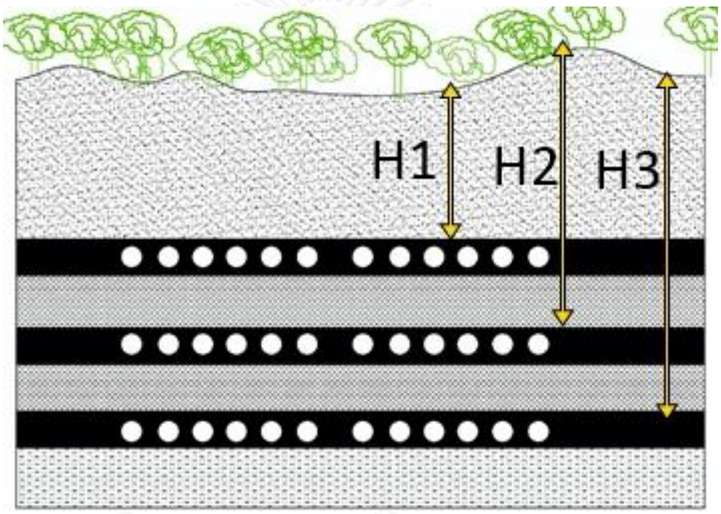


Figure 2-8: Multi passes of the augering system [27].

Shimada et al., [5] claimed that the auger diameters are between 0.5 to 3.0 meters with the working per crew is about 2-3 people and an augering system is faster both enrolling into the seam and the movement. Auger miner can recover just about 30% of the total coal in the seam which is one fourth the amount of the continuous miners does (Figure 2-9). An auger miner can access into thin coal seams, between 0.9 to 1.8 meters [28].

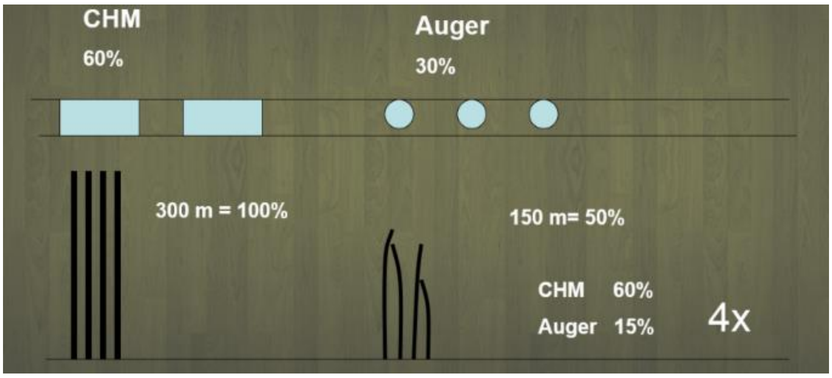


Figure 2-9: CHM and AHM miner recovery ratio [17]

2.2.2.1 Pillar design in auger highwall mining

The rectangular system has already been developed and applied in mining sectors in such countries as the US, Australia, India and New Zealand, and currently, mining engineers are trying to transform this design technique to be applicable in augering system. Web and barrier pillar designs in an auger mining system would not be much different from the continuous highwall mining design. In this research, the author is trying to apply the empirical modeling of Mark-Bieniawski, Salamon Monro and UNSW in an augering system. Somehow, the numerical modeling by FLAC3D will help to check whether these equations can be applied in this weak geological condition or not by comparing the result from FLAC to that from the theory.

2.2.2.1.1 Web pillar design

The Mark-Bieniawski formula on the narrow rectangular pillar is too small to the penetration length is used. Figure 2-7 shows the geometry of auger mining system.

- **Pillar strength**

The three equations in Table 2-2 are taken to design for the auger mining pillar strengths. In this case, some parameters are keeping the same excluded the pillar height (*h*) which is replaced by the auger diameter. The strength equations will be:

Table 2-3: Pillar strength estimation in auger highwall mining

	Strength formulae	Original	
Mark-Bieniawski	$S_P = \sigma_C(0.64+0.54\frac{W_P}{D})$	USA (1999)	Eq. 10
Salamon Munro	$S_P = \sigma_C \frac{W_P^{0.46}}{D^{0.66}}$	South Africa (1967)	Eq. 11
UNSW	$S_P = \sigma_C \frac{W_P^{0.52}}{D^{0.84}}$	Australia (1996)	Eq. 12

- **Pillar Stress**

The stress on web pillar is calculated in a similar manner as the continuous highwall pillar stress. In the case of auger mining, the opening W_E is replacing by the hole diameter (*D*). The actual stress of pillar is presented as in the Eq.11.

$$\sigma_P = \sigma_v \cdot (\frac{W_p + D}{W_p}) \qquad \text{Eq.13}$$

Generally, the ratio of strength to stress is the factor of safety. Then factor of safety SF_P of web pillar in the augering system is performed as the strength divided by the stress of web pillar.

$$SF_P = \frac{S_P}{\sigma_P} \qquad \text{Eq.14}$$

Usually, the safety factor of web pillar is ranged from 1.3 to 2.0 depending upon the regional geology and further usage of the surface [13]. However, NSW DEPARTMENT OF PRIMARY INDUSTRIES of Australia proposed that for any coal mines which have no detail guidance, the minimum safety factor 1.6 is suggested [27].

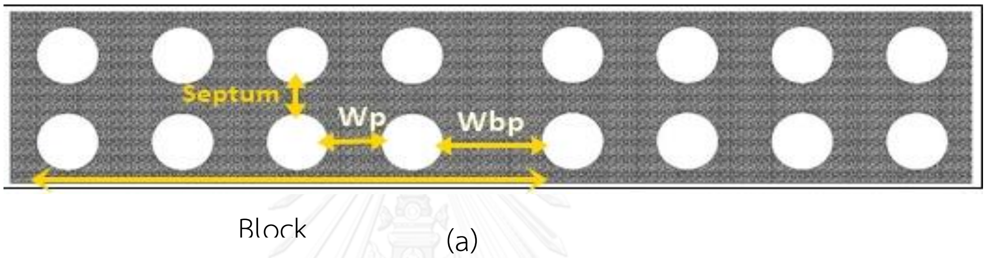
2.2.2.1.2 Barrier pillar design

Barrier pillar prevents extend of collapse at the adjacent panel is there occur any pillar collapses of the pillar. The strength of barrier pillar (S_{BP}) is the same as those representing in Table 2-3 by just replacing web pillar width to barrier pillar W_{BP} and the stress loaded on barrier pillar are calculated the same as Equation (8). However, the panel width is calculated as:

$$W_{PN} = N(W_p + D) + D \qquad \text{Eq.15}$$

The highwall pillar, since it was already assumed that the web pillars were collapsed, the safety factor can be taken as low as 1.0. The factor of safety is given as:

$$SF_{BP} = \frac{S_{BP}}{\sigma_{BP}} \qquad \text{Eq.16}$$



(a)

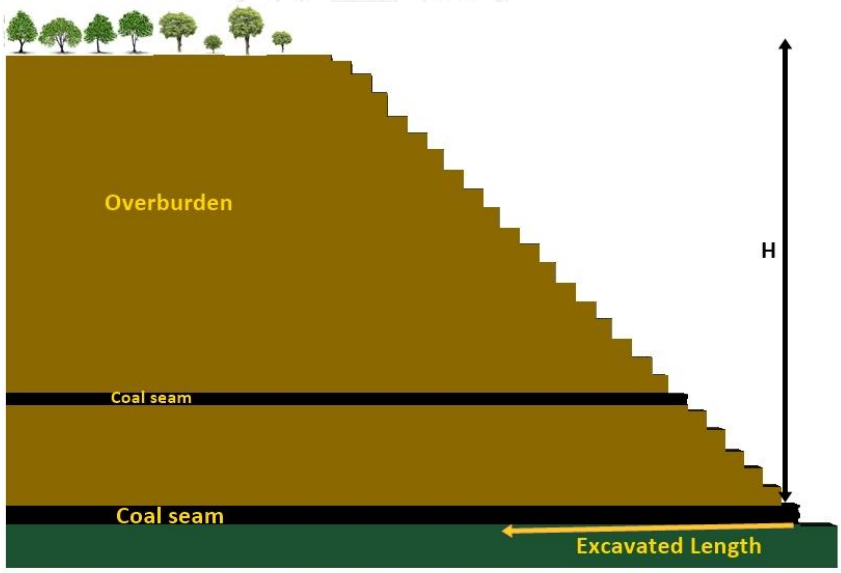


Figure 2-10: (a) front view of auger highwall and (b) the side view of geometry auger highwall of Mae Tan Coal Mine

The laboratory test on the pillar strength for circular hole carried out at the series of Indonesian coal mines. The dimensions of the specimens were 200 mm thick, 200 mm width and 150 mm high (Figure 2-11). The specimens consisted of gypsum, cement, and water (weight ratio of 1:1:1) were dried three days and applied the test. They have 50 mm circular and rectangular opening, four pillar widths of 25 mm, 50 mm, 75 mm and 100 mm were then evaluated. The pillar strength index is calculated as [25]:

$$\text{Pillar strength Index} = \frac{\text{Failure load}}{\text{Cross section of pillar} \times \text{UCS of material}} \qquad \text{Eq.17}$$

And the pillar strength for the circular opening was stronger than the rectangular system. This result showed that the pillar strength in the auguring system would be higher than that in rectangular one.

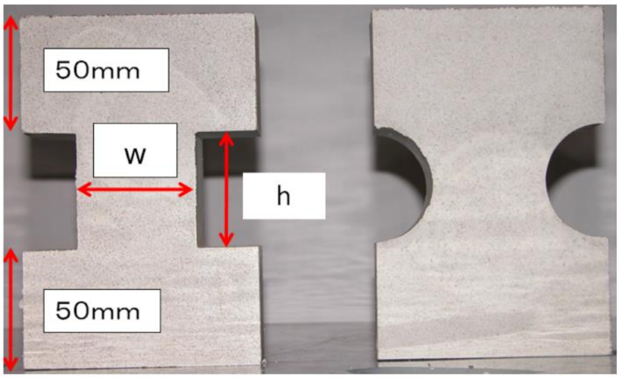


Figure 2-11: Specimens for laboratory tests (left; square openings, right; circular openings).

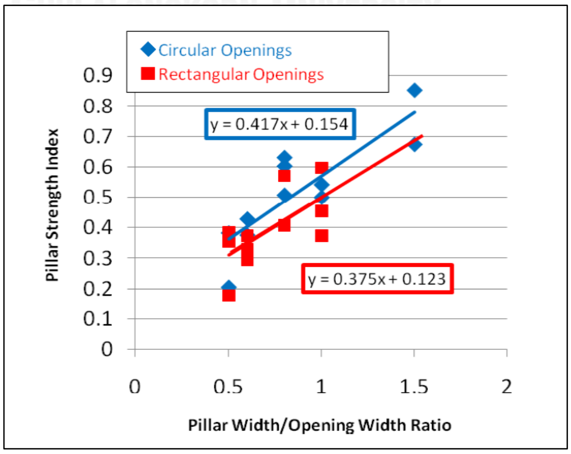


Figure 2-12: Relationship of strength index and pillar width and opening width ratio.

2.2.3 Productivity of auger highwall mining system

In this section, the author focused on the percent recovery of coal, and the amount of producing coal. The recovery ratio is one factor measuring the economic effectiveness. However, the tonnage of coal must be importantly included in this highwall design. The recovery ratio (*%R*), and coal production (*T*) per drilling hole are expressed in the following equations. The augering system drills as the circular hole openings (Figure. 2-10 (a)) such the same as the cylinder shape. The combination of cylinder volume to the coal specific gravity is called tonnage of coal.

Both tonnage and percent recovery are derived from the basic mathematics of cylinder volume calculation because the auger hole is actually the inclination cylinder lied down parallel to the coal seam. The height of the cylinder is converted to the penetration length of auger rolling into the seam symbol as *L* with the diameter of the hole is *D*. The ratio of extracted area to the box area is the recovery ratio (Figure 2-13). If the percent recovery is high but the quantity of mined coal is less, it would never provide one best economic attention. However, it is said similarly about the economic consideration if the quantity of mined coal is huge but the percent recovery is less. So the next equations are indicated those necessary parameters. The recovery ratio and tonnage of coal per extracted box are presented in Eq. 18 [29] and Eq. 19 respectively.

$$\%R = \frac{\text{Area of hole}}{\text{Area of effective block of coal}} \text{ or } \%R = \frac{\pi D^2}{4} / \left[(D + W_p) \times h_c \right] \qquad \text{Eq.18}$$

$$T = A \times L \times \gamma_c \qquad \text{Eq.19}$$

Where A, h_c, γ_c and L are the extracted area, coal seam height, specific gravity of coal and effected drilling length.

2.3 Rock property

The standard testing is promoted for such mechanical properties as tangent modulus, Poison's ratio, cohesion, friction angle, tensile strength, uniaxial compressive strength, shear and bulk modulus for the rock in roof and floor. The uniaxial compression test provides the UCS of coal and rock roof and floor. Other properties which have not been given from the company were estimated from the existed data. Poisson's ratio was assumed to be 0.25 for both coal and rocks while tangent modulus and tensile strength were roughly estimated from UCS for sedimentary rock [30, 31]. Shear and bulk modulus can be calculated from young's modulus and Poisson's ratio.

Table 2-4: Rock property variables

Variables	Formula	References	Equation number
σ_c	$\frac{P}{A}$	[32]	Eq. 20
E	$80 \cdot \sigma_C^{1.91}$	[30]	Eq. 21
G	$\frac{E}{2(1+\nu)}$		Eq. 22
K	$\frac{E}{3(1-\nu)}$		Eq. 23
σ_t	$\frac{1}{10}\sigma_C$	[31]	Eq. 24

2.4 Computer modeling feature

In FLAC modeling, the mechanical properties are combined averaged for top soil, roof, coal seam or floor to be simplified. This computer modeling is an important feature to demonstrate the stress distribution on the highwall system and FISH function is coded to generate the pillar strength. From 3D modeling for highwall mining, the stress distribution on the highwall is varied due to the depth variation. The deepest depth of overburden generates greater stress concentration on the pillar. So FLAC3D modeling performs the exact feature of the stress-strength analysis. Later on, the factor of safety of both web and barrier pillars can be calculated where it is next used to compare with the empirical modeling. The analysis was carried out under these initial conditions:

- Grid generation.
- Initial boundary condition response was the roller along the sides and the bottom of the model (Figure 2-12).
- The elastic-plastic material was selected for stress simulation and strength-softening material was used to estimate the pillar strength.
- Gravity and body load were applied with the gravity acceleration of 9.81 m/s^2.

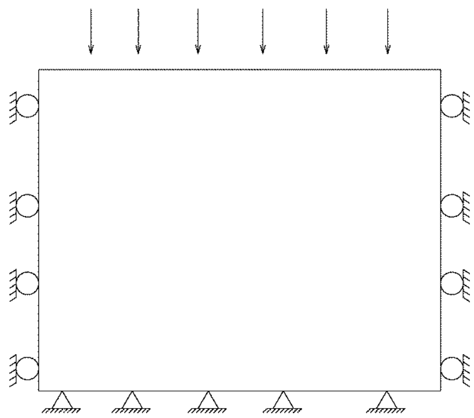


Figure 2-13: Boundary condition in FLAC3D.

CHAPTER 3
METHODOLOGY

The procedure of work for this dissertation has been described in this section. The study is separated into various sections for more details. The design of highwall stability was the main purpose of the research including the investigation of the coal production from this mine was the second purpose.

The first section is the investigation on web pillar design which is a parameter for the next analysis. In the section of web pillar design, different criteria are proposed to observe on differentiation on stress and strength of the pillar. After the first portion done, barrier pillars were designed. The same concepts as web pillar, both numerical and empirical results were compared.

3.1 Rock properties

According to Figure 1-3 in Chapter 1, there are six types of rock divided into layers with different depths. The main component of the rock strata can be conducted into three categories: the roof, coal seams and the floor. Roof or floor is the upper or lower rocks of the coal seams. Rock properties for each layer are represented in Table 3-1 below. These mechanical properties are very important for both empirical and numerical analyses. For empirical analysis, density and layer height are very crucial for the calculation. For numerical analysis, shear and bulk modulus, density including cohesion and friction angle of the rocks.

Table 3-1: Rock Properties of Mae Tan Mine

Rock Types	**Density**	**σ_c**	**Cohesion**	**Friction Angle**	**v**	**E**
	g/cm^3	MPa	MPa	Deg		GPa
Top soil	2.0	1.0	0.2	15	0.25	0.080
Sandstone	2.3	5.0	2.8	20	0.25	1.730
Shale	2.3	7.5	2.0	20	0.25	3.754
Ball Clay	2.2	6.5	2.3	18	0.25	2.856
Carbonaceous shale	2.2	6.9	0.1	10	0.25	3.201
Coal	1.25	4.0	1.8	20	0.25	1.130
Rhyolic Tuff	2.7	30	10	25	0.25	53.0

3.2 Research methodology structure

The designs have been set into three categories: single pass, double passes, and multi passes. The main components for these categories are the pillar stabilities based on the concepts of stress-strength investigation. Both empirical and numerical analyses were conducted to optimize the design. Figure 3-1 below is illustrating the methodology structure. In this structure, the single pass is the first category, secondly, is the double passes and the last one is the multiple passes. Each layout can be expressed in Figure 2-6, 2-7 and 2-8 as the single pass, double passes and multiple passes respectively in Chapter 2.

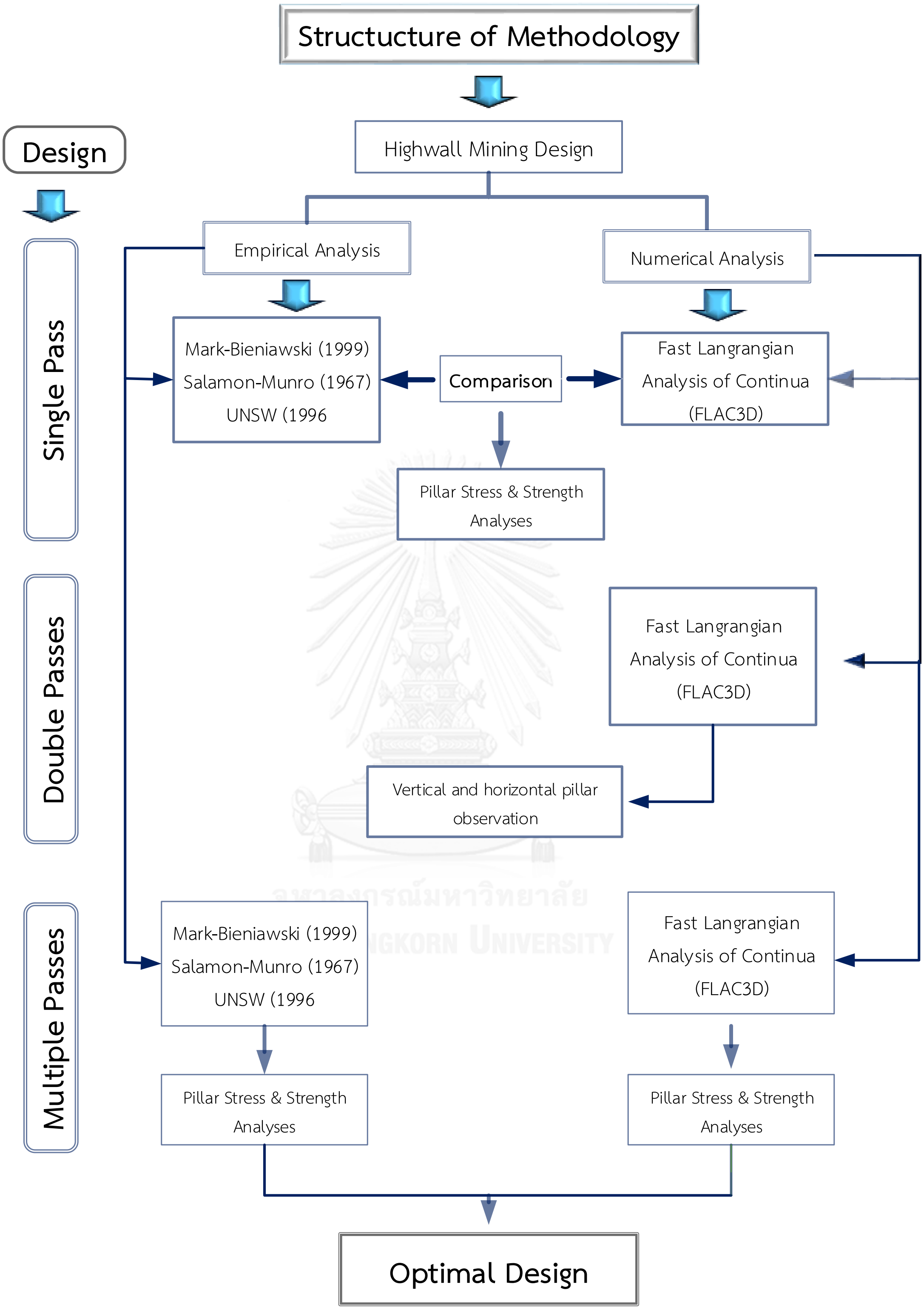


Figure 3-1: Methodology Structure of the dissertation

3.2.1 Single pass

The single pass is defined to have only one row of the hole. For this single pass, both numerical and empirical analyses were assessed to design on the strength and stress ratio. The empirical was focused on three well-known equations from the US (Mark-Bieniawski), South Africa (Salamon-Munro) and from Australia (UNSW). The reason to select these equations in the study because most of the empirical equations were obtained from the specific study for each region. So those factors included in each equation were based on the real geological condition and coal strength properties. Moreover, the numerical analysis was also conducted for the single pass design at Mae Tan coal because the best way is to figure out the optimal method in the design. In addition, Mae Tan coal is weak coal as the reality. The design parameter for the single pass is shown in Table 3-2. The auger diameters of 1.5 m, 1.9 m and 2.1 m were selected according to the types of commercially available machines [33]. The designed web pillar widths were between 0.5 to 4.0 meters with the interval of 0.5 m. The stress loaded on the pillars were investigated along pillars from the shallowest to the designed deepest length until 100 m. According to Figure 1-2, coal seam lengthens to 120 m from the pit to the gob of the highwall. Since this coal is not so strong, the estimation of mined drilling length will not longer than 100 m. After that the stress distribution on the pillars has truly depended on the overburden rock and pillar widths as well as the diameter (D) of the auger machine. The safety factor of 1.6 was set up as this design (following the recommendation from Technical Reference Mine Safety CTR-001 of Australia “For a Notification of Highwall Mining and Auger Mining (As a High-Risk Activity”), [27]. For barrier pillar, pillar widths of 3, 4 and 5 were directed to design and safety factor of 1.0 was set as the stability baseline.

Table 3-2: Single pass criteria design

Parameter Input:								
Web Pillar widths (m):	0.5	1	1.5	2	2.5	3	3.5	4
Barrier Pillar widths (m):		3	4	5				
Diameter (m):		1.5	1.9	2.1				
Designed Safety Factor of Web and Barrier Pillar:					1.6	1.0		

3.2.1.1 Empirical analysis of single pass

Table 3-3 is the empirical calculation from a case of the auger diameter of 1.5 m and pillar width of 0.5 m. The vertical stress (σ_v) was the result of the average density used for the upper rock layers subjected on the coal seam multiplied by the depths of the overburden rock (Eq. 2-5), and then S_P and σ_P are the strength and stress of the pillars correspondingly. The factor of safety was followed Eq. 2-6 which is the ratio of pillar strength to pillar stress. The design was observed along 100-m drilling length in the lowest coal seam for the single pass. Since the overall slope angle of this open pit mining is 45°, so by simplifying the geometry in the model, the vertical depth (***H***) was supposed to be equal to the horizontal depth (***L***). The different depths provided different vertical stress and strength of the pillars.

3.2.1.2 Numerical analysis of single pass

The computer modeling is an important feature to demonstrate the stress distribution on the highwall system and FISH function is coded to generate the pillar strength. From 3D modeling for highwall mining, the stress distribution on the highwall is varied due to the depth variation. The deepest depth of overburden generates greater stress concentration on the pillar. So FLAC3D modeling performs the exact feature of the stress-strength analysis. Later on, the factor of safety of both web and barrier pillars can be calculated where it is next used to compare with the empirical modeling. Because the drilling length is up to 100 m, the average stress subjected on this long pillar is curved by sectioning the long pillar into 10 m each by applying the different initial stresses on the sections. The details will be presented in the next chapter.

3.2.2 Double passes

The double passes are the technique of the application of two rows of the auger holes. The parameters and in the double passes design had been set up (Table 3-3). There were not many as in the single pass. Only auger diameter of 1.5 m was selected to design for this double passes. Pillar width of 1.0 m and 1.5 m were investigated as the vertical pillar widths. However, it the horizontal width or distance between two holes is also a risk decision. In this case, the vertical distance between holes was arranged to 0.8 m and 1.0 m in order to analyze. In addition, the number of web pillars in a panel is still important for the final panel design. This time, the value of N was set to be 1 and 2 coming along with 2 m of barrier pillar width. For the stability of this system, the factor of safeties was observed into 3 main items, the hole sidewall where the maximum stress concentrated, vertical and horizontal pillars as shown in Table 3-3.

Table 3-3: Criteria design for double passes

Diameter	1.5	
W_P	1.5	
W_{BP}	2	
Vertical distance between holes	0.8	1.0
N	1	2
Safety Factor		
Hole sidewall	1.0	
Vertical Pillar web pillar	1.6	
Horizontal Pillar septum	1.6	

Adopting to the same concept of the single pass design, stress and strength of the pillars were analyzed. None empirical approaches mentioned clearly that the application of those empirical methods is acceptable to the double passes of the augering system. Responding to this problem, only numerical modeling was played the role for this double passes design. The numerical layout was created as the full model of the open pit highwall as shown in Figure 3-2 and Figure 3-3, then the stability was investigated.

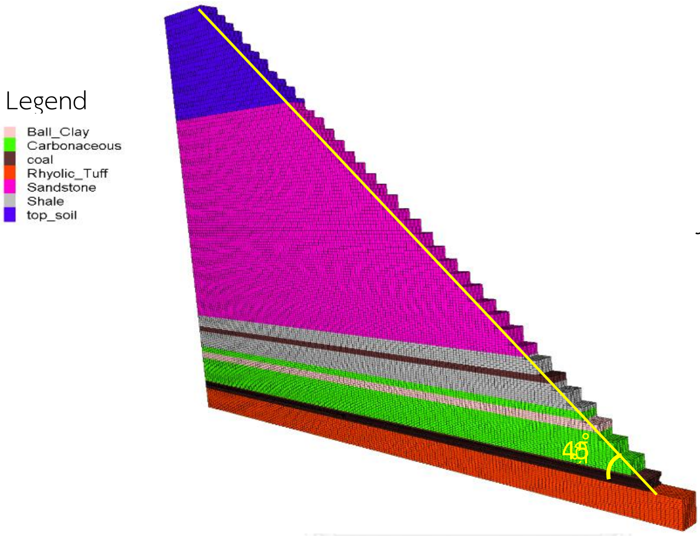


Figure 3-2: Full model for double passes design

The two types of pillars in double passes are demonstrated in Figure 3-4 below:

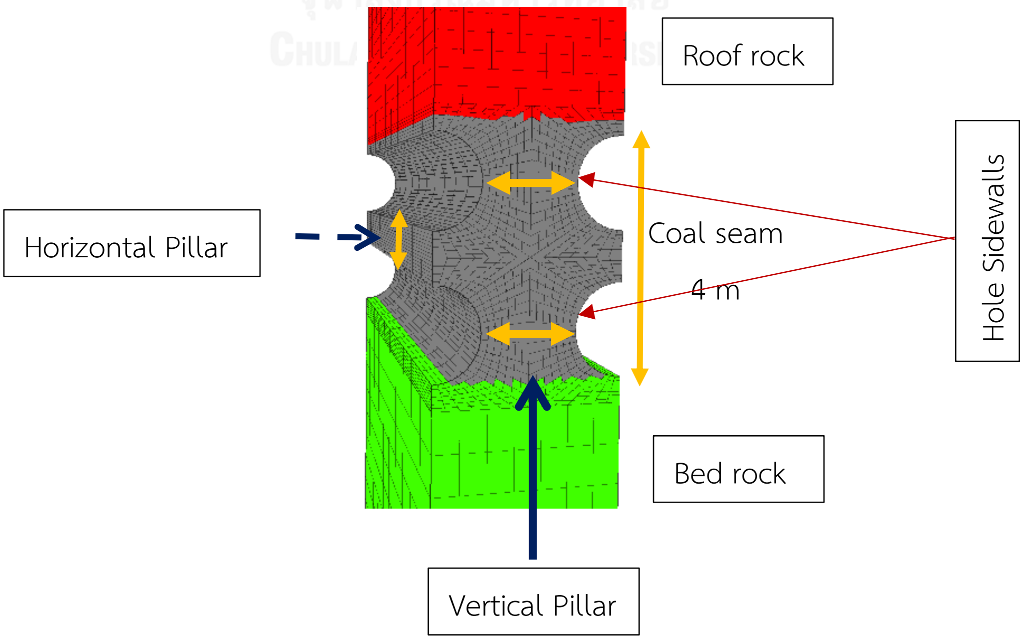


Figure 3-3: Pillar system in double passes

- **Vertical pillar**. In this case, the strength of pillar was estimated following the single pass system. For stress on the pillar, it was estimated according to the stress distribution on the pillar such as: between upper holes, in the middle of the pillar and between lower holes. After that, the average stress was come up.
- **Horizontal pillar**: The stability of the horizontal pillar was estimated using the horizontal stress from FLAC3D by comparing to the strength from the numerical as well.
- **Hole Sidewall**: If the depth is in the medium-high, mostly, the high stress is distributed around the mouth's holes. However, since the depth more increases, the stress distribution is developed toward the center of the pillar which is meant that the pillars may not be more stable are its strength is not high enough to react to this stress. In this stability estimation, the vertical stress on the pillar was used to compare with the pillar strength from the numerical modeling.

3.2.3 Multiple passes

Multiple passes are the application of auger miner into upper and lower coal seams. The optimum auger diameters from the single pass and double passes were taken to design. The design is divided into two auger diameters, 1.5 m, and 2.1 m. The final comparison of the two diameters is the final selection pattern. Table 3-5 is the design criteria for the multiple passes.

For the auger diameter of 1.5 m, the designs will be divided into 2 types, the single pass for the first layer and double passes for the second layer. The double passes design items are mentioned in Table 3-4. The single pass design for the auger diameter of 2.1 m is followed the existing generated data from the single pass design in section 3.2.1.

Table 3-4: The design criteria for multiple passes

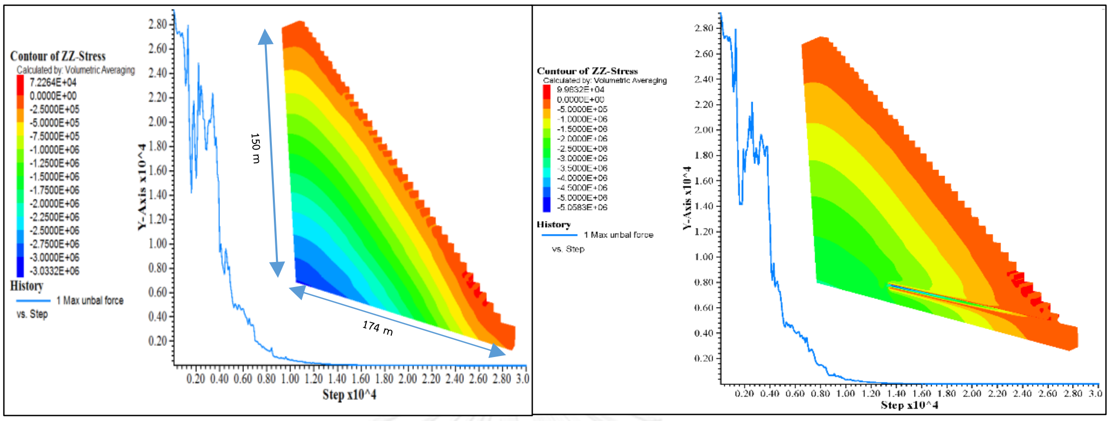
D=1.5 m						
Seam	Design	Wp	W_{BP}	N	SF	
					Web pillar	Barrier Pillar
Upper	Single pass	1.5	2	1	1.6	1.0
Lower	Double passes	Design reference from Table 3-4				
D=2.1 m						
Upper	Single pass	2	3	1	1.6	1.0
Lower	Single pass	2	3	1	1.6	1.0

CHAPTER 4
RESULT AND DISCUSSION

When a highwall mining is developed from the existing surface, the pillar and highwall supports are the main factors to stabilize the highwall. For this reason, pillar designs are taken into account mainly of the study. Web and barrier pillars have different functions in supporting the highwall system. Both of these pillars must be well designed to prevent any collapses for now and even in the future. There are many pillar strength formulae which have been proposed by different researchers for specific coal mines coming along with their local geologies. There are some shortcomings to apply these equations directly for Mae Tan coal. The consequence, the comparisons of the empirical equation to the numerical 3D modeling of FLAC3D were studied in order to construct the solution for Mae Tan coal. The analysis was done into two parts, for web pillar and barrier pillar.

4.1 Stress state for underground excavation

There is the change of stress loaded on the system after the excavation finished. The greatest stress is located at the deepest point for the initial state, however, the stress state on the pillars becomes greater after the holes were excavated. To demonstrate this fact, the model of 150-meter deep, 174-meter long and the slope angle of 45 degrees was constructed. The web pillar width of 2 meters and 100-meter-entry holes of 2.1 meters were modeled as an example to demonstrate the stress state for underground excavation. The analysis procedure was done until the equilibrium state reached for both initial and after excavation. The stress subjected on the pillar was then observed from the beginning of the pillar at the slope face until the end of the pillars. The stress concentrated on the pillars changed from the minimum to the maximum at the end of the pillar because the overburden height increased. The differentiation of stress on the pillars is illustrated in Figure 4-1. The stress value was figured out by the contour of the stress at various colors. The dark blue is the highest stress value. The maximum stress of the initial state was about 3 MPa then, after the auger excavation, the stress was increased to about 5 MPa. The maximum stress also moved to concentrate on the pillar instead of locating on the deepest point of the system.

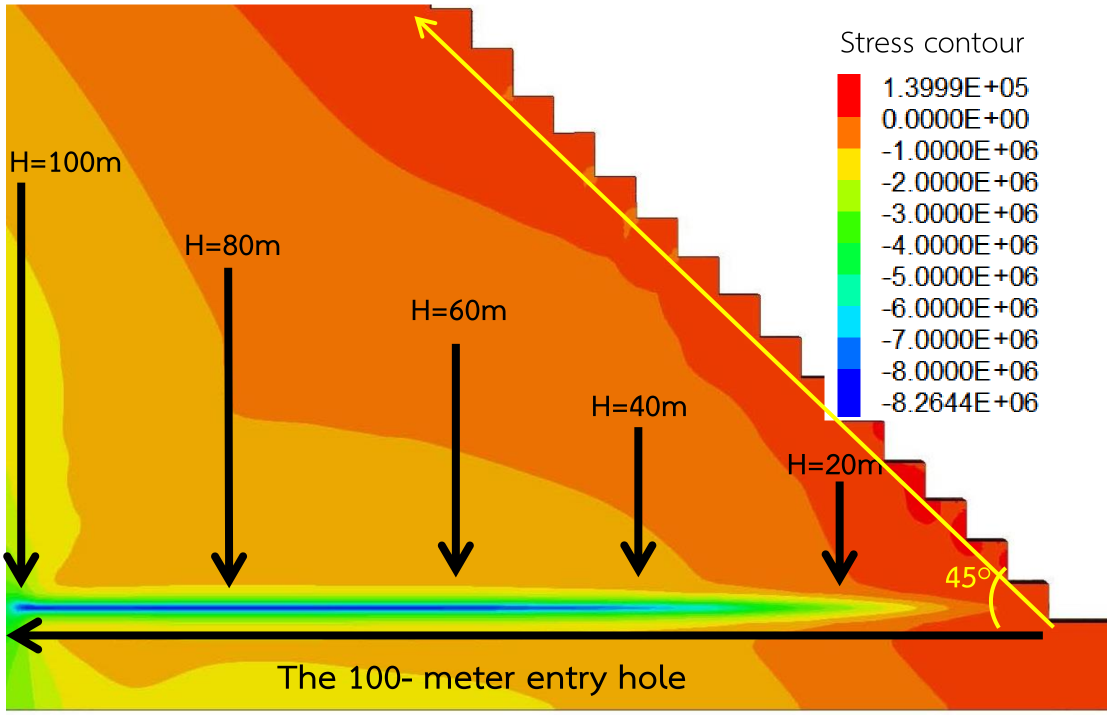


(a) (b)

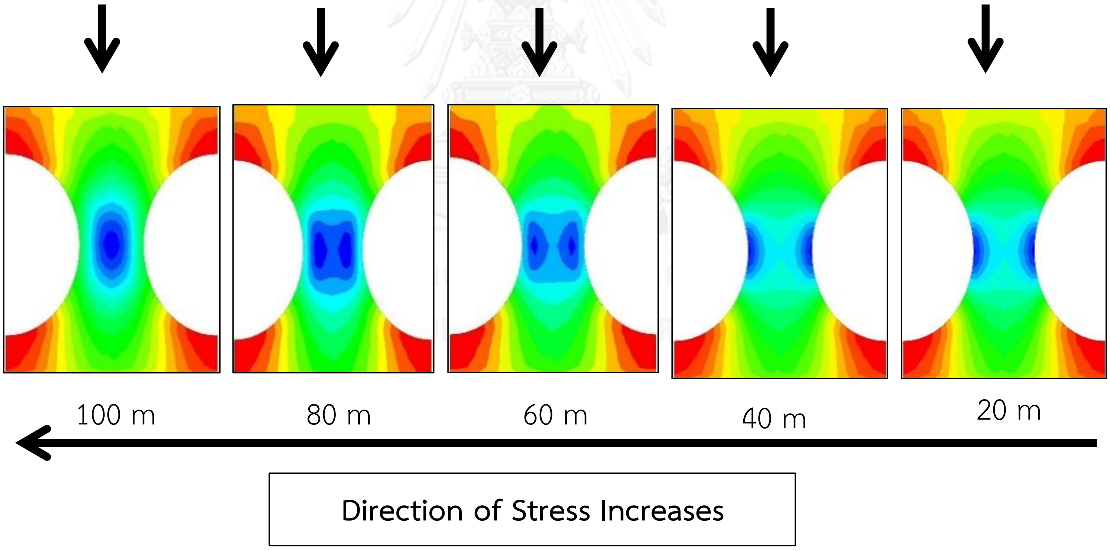
Figure 4-1: 3D-stress analyses of Auger highwall mining; (a) Stress on the system before excavation, (b) Stress concentrating on web pillar after excavation

4.2 Stress development along the pillar

The maximum excavated length of 100 meters was analyzed. The non-uniformed stress distribution on the pillar was expanded greater when the depth increases. The overall pit angle of this open pit mining is 45°. By simplifying the model, the overburden depth was set up equal to the penetrated length (Figure 4-2 (a)). This really clarifies that the depths increased if the penetrated length increased. The development of stress on the pillar with different level of overburden is illustrated in Figure 4-2 (b). After the stress analyses were finished, the results showed that at the lower depth, the stress concentrates mainly on the hole sidewalls, then it develops larger and larger towards the middle of the pillar.



(a)



(b)

Figure 4-2: (a) The auger mining layout with the drilling hole of 100 meters and (b) the development of stress along the pillar due to the depth increases.

4.3 Numerical stress analyses

Since there were 100 meters of the pillar, the pillar was cut into several sections of 10 meters each to be analyzed. According to this, there were 10 sections of the pillar having been created.

There is the difficulty of pointing out the specific location on the pillar to demonstrate the stress value (Figure 4-3). Therefore, the average stress of the pillar was analyzed. Different initial stress was applied in FISH-pillar model to establish the different peak loads for different sections of the pillars as illustrated in Figure 4-4. The vertical axis was the stress loaded on the pillar and the horizontal axis of the graph is the steps for a case of the auger diameter of 1.5 m and the pillar width is 0.5. The maximum stress was at the end of the pillar which was about 8 MPa. At the pillar length of 10 m or at the depth of 10 m, the stress loaded on the pillar was only about 0.8 MPa. Figure 4-4 is demonstrating the stress state for the different length of the pillar as well as the different height of the overburden. The numerical stress in y-direction was plotted with the steps as x-direction.

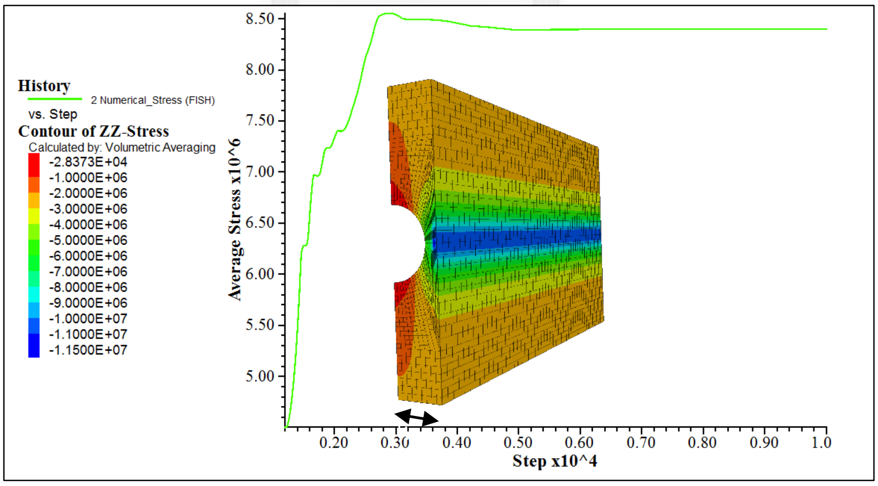


Figure 4-3: The half model of pillar for the average vertical stress on pillar section of 10 m.

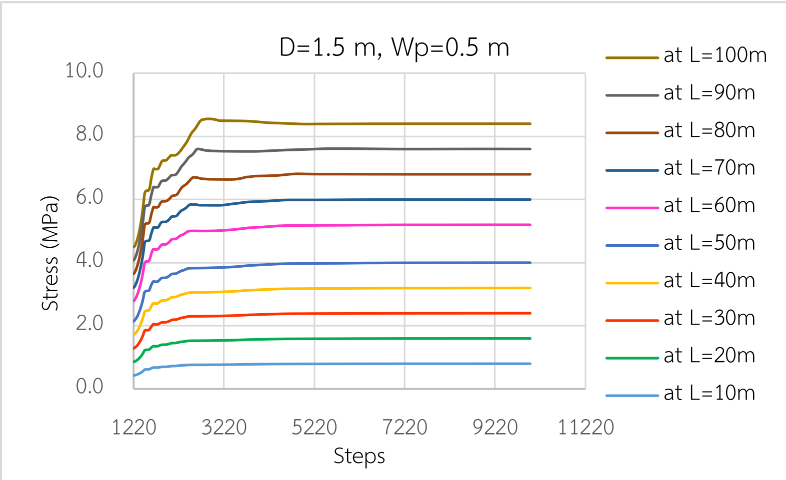


Figure 4-4: The average stress on the section of the pillar for auger hole 1.5 m and pillar width of 0.5 m

The numerical layout for barrier pillar simulation was built in the condition that web pillars were assumed to be collapsed. Supposing that the panel system is shown in Figure 4-5. Then it will leave a big room as demonstrated in Figure 4-6. This highwall support was also segmented as the small pillar sections in 10 meters each to evaluate the average stress.

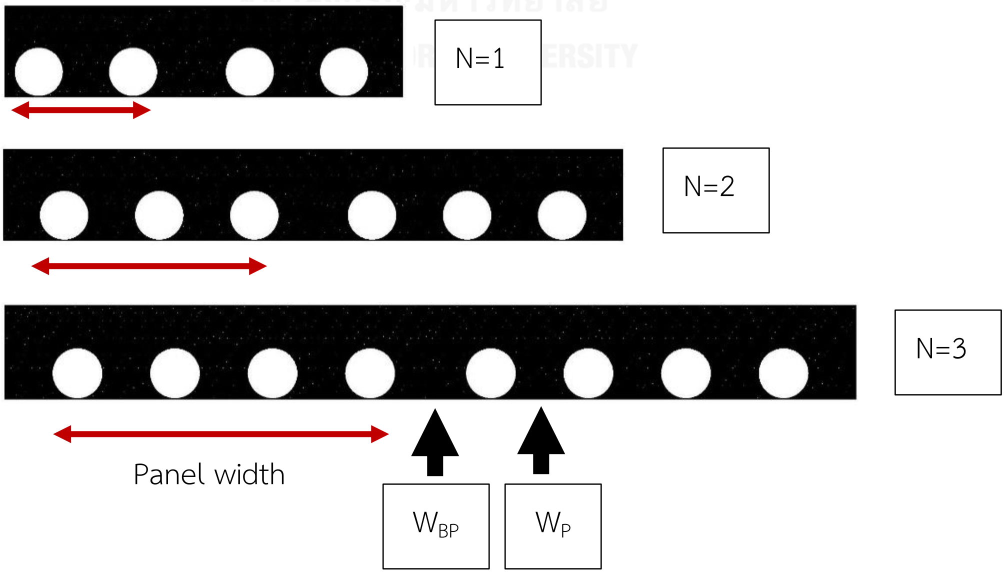


Figure 4-5: The average stress curve on barrier pillar section.

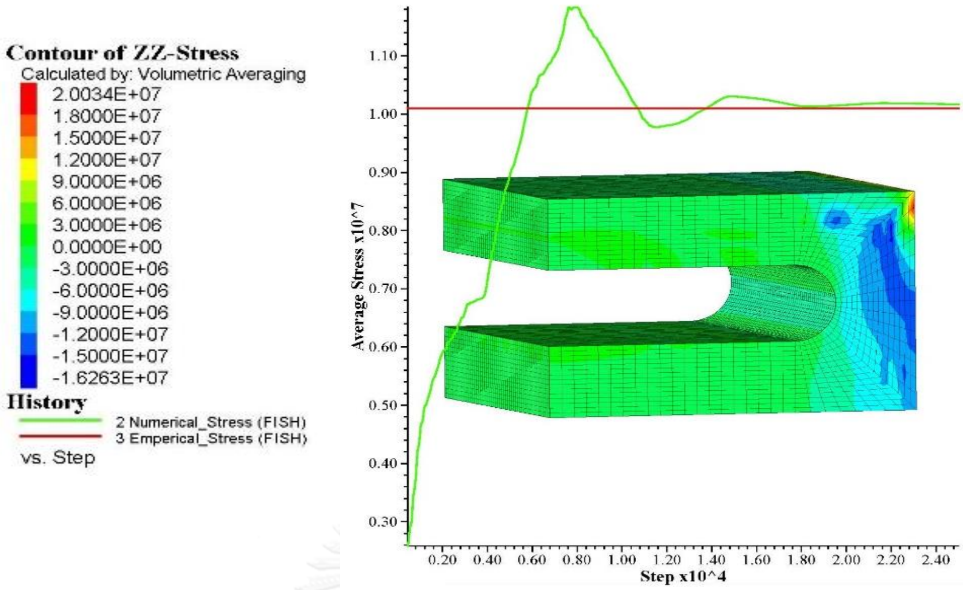


Figure 4-6: The average stress curve on barrier pillar section.

4.4 Numerical Strength Analysis

Similar to the stress analysis, the strength of pillar was then estimated from the numerical modeling. In web pillar design, there were 24 cases of strength taken to be investigated in numerical modeling including 3 more cases for barrier pillar design. These are all cases for the design of the single pass.

These cases were for various widths of web and barrier pillars in order to carry out an ultimate solution. The special FISH-function for pillar was established to examine the pillar strength including the input mechanical properties of rock into the model. The maximum peak strengths from numerical analysis were then taken to compare with the strengths from the empirical calculations in order to select one appropriate method applied in this mine. After that, the stress-strain curve was obtained as indicated in Figure 4-7. Be noted that, the underground water was not included in this design and the pillar was designed as the horizontal pillar. So in this design, the simplified model was created for the horizontal pillars.

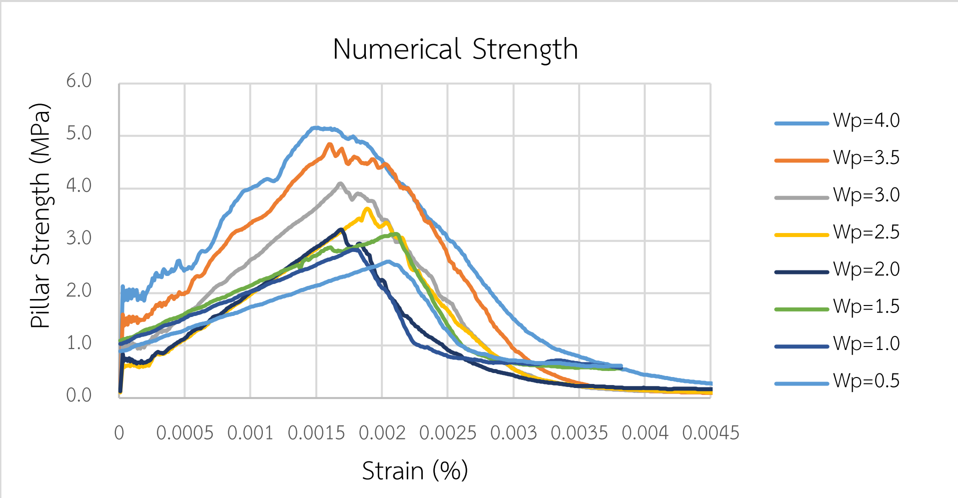


Figure 4-6: The relationship between pillar strength and pillar strain in a case for auger diameter of 2.1 m.

4.5 Single pass design

There are two types of pillars for the auger highwall mining, barrier and web pillar. Web pillar will be optimized according to the different types of auger diameters and barrier pillar will be designed after the optimization of web pillar. Both numerical and empirical modeling will be included for web and barrier pillar design and then the comparison of the result from the analyses was made. After that, one method was selected to use for this mine design. For web pillar design, the case of auger diameters 1.5 m, 1.9 m and 2.1 m were analyzed for the numerical as well as the empirical analyses.

4.5.1 Case of auger diameter 1.5 m

4.5.1.1 Comparison of numerical and empirical stress

There were 80 models analyzed by the numerical method to find the stress in the case of auger diameter of 1.5 m. There were 10 sections of the pillar for a case of pillar width and there were 8 cases of pillar widths taken into the modeling in FLAC3D.

Referring to the results from both analyses, the stress from the numerical analysis provided similar results to the empirical equations. In fact, the stress from numerical method provides a bit smaller values than the results from the empirical equation. This can be expressed that the application of the distributary equation of stress can be used directly. Figure 4-8 and Figure 4-9 are the results of the stresses from the empirical and numerical analyses respectively.

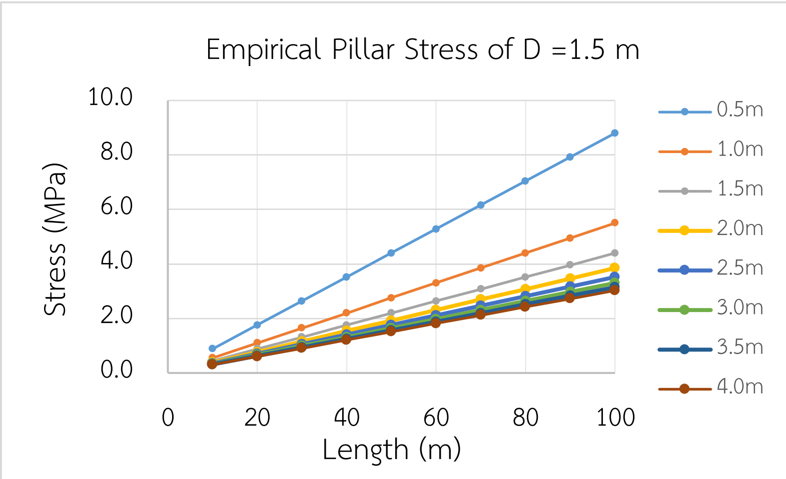


Figure 4-7: The empirical stress analysis for auger diameter of 1.5 m

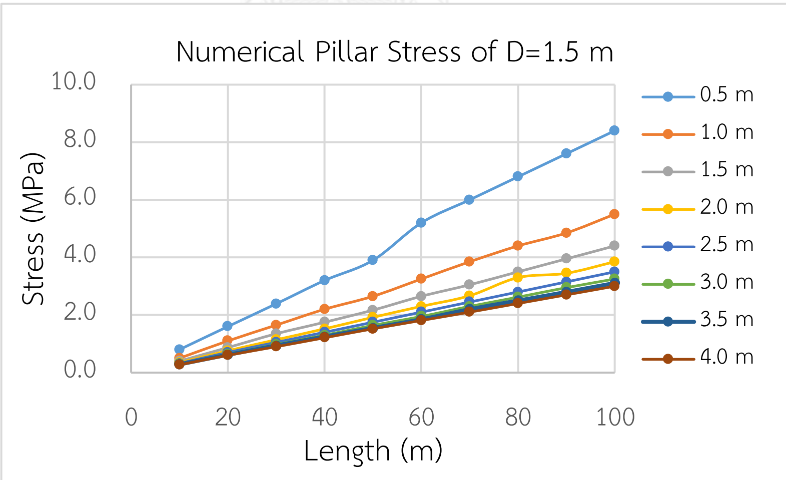


Figure 4-8: The numerical stress analysis for auger diameter of 1.5 m.

4.5.1.2 Comparison between Numerical and Empirical Strength

In strength analyses, there were 8 cases tested in numerical modeling. The pillar heights in the study of auger mining are equal to the auger diameter. In this special case, auger diameter was 1.5 m and then the variation of web pillar widths were between 0.5 m to 4 m with the interval of 0.5 m. Then diagram showing about the strengths of different web pillar width for the auger diameter of 1.5 m is shown in Figure 4-10.

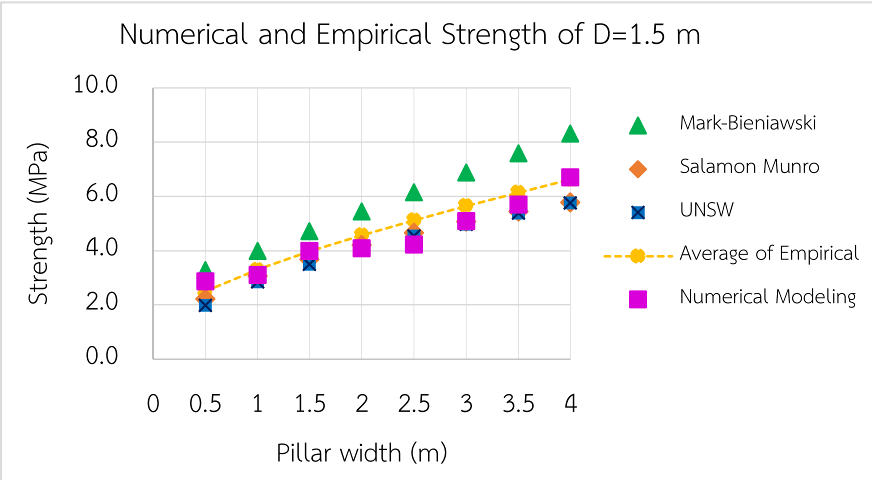


Figure 4-9: The numerical strength for the pillar for auger diameter of 1.5 m

On behalf of Figure 4-10, Mark-Bieniawski theory always provides the larger strength than Salamon-Munro and UNSW as well as the strength from numerical modeling. In other words, the results from numerical modeling were exactly similar to both South Africa and Australia's equations. In the same manner, almost the average strength of empirical theories was really close with the results of the numerical method. So it can be proved that the average strength of theoretical mathematics can be applied to next steps.

4.5.1.3 Comparison between Numerical and Empirical Safety Factor

After the stress and strength were finished the analyses, the safety factors of each case were calculated. The ratio of pillar strength to stress is the safety factor. Figure 4-11 represents the saf ety factors from all cases of web pillar widths from the average empirical equation and Figure 4-12 is representing the factor of safety from the numerical analyses of all cases of the web pillar widths. The value of stability factor from both Figure 4-11 and 4-12 did demonstrate that they were approximated to each other. According to the results discussed above, the application of average empirical theory cab be used for the case of the auger diameter of 1.5 m.

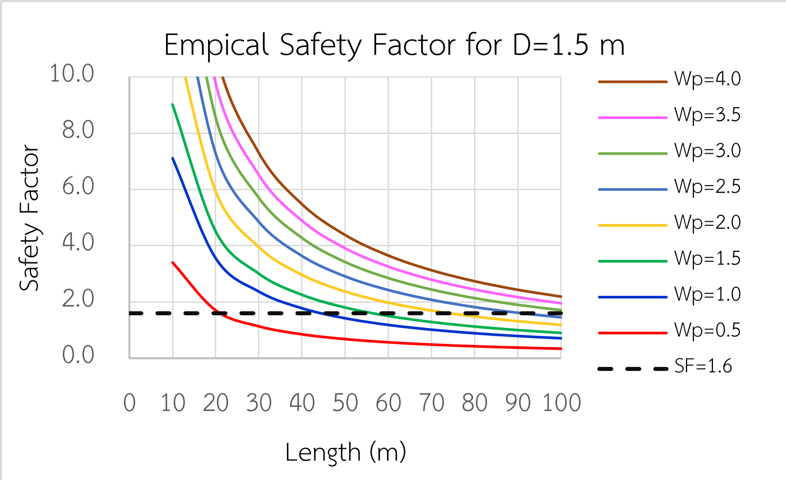


Figure 4-10: Safety Factor from Empirical Analyses for auger diameter of 1.5 m.

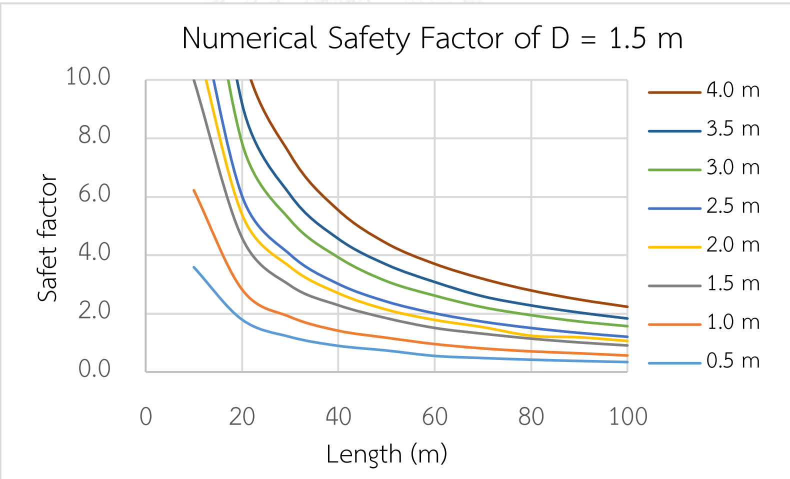


Figure 4-11: Safety Factor from Numerical Analyses for auger diameter of 1.5 m.

4.5.2 Case of auger diameter of 1.9 m

Following the same procedures of the previous section, 80 cases of stresses were investigated in numerical analyses. Same as before, every pillar was sectioned in

10 meters each to estimate the average stress on the pillar for every 10 meters. The results from both analyses are demonstrating.

4.5.2.1 Comparison between numerical and empirical stress

For the auger diameter of 1.9 m, the stress was analyzed from the numerical and empirical methods which are the same as the auger diameter of 1.5 m. Figure 4-12 is figured out the stress from the empirical equation and Figure 4-13 is the graph of stress from the numerical analysis.

According to Figure 4-13 and 4-14, the results of stress were very similar to each other. In some cases, the numerical stress was greater than the results from the equation stress results, on the other hand, some results from the empirical calculations were bigger than from the numerical estimation.

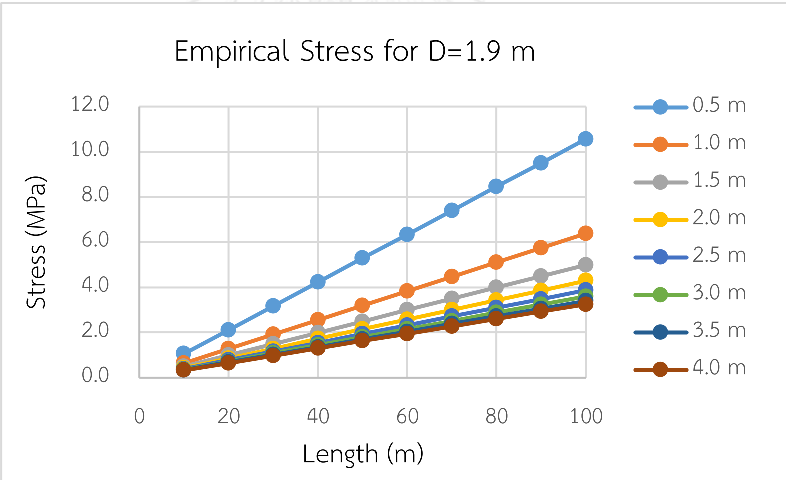


Figure 4-12: The empirical stress analysis for auger diameter of 1.9 m

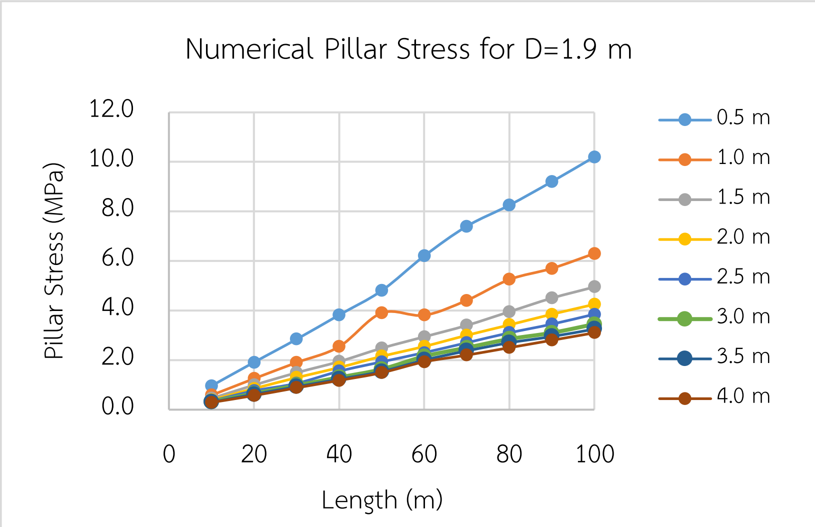


Figure 4-13: The numerical stress analysis for auger diameter of 1.9 m

4.5.2.2 Comparison between Numerical and Empirical Strength

There are 8 cases of strength taken to be studied in the numerical analyses. The pillar height was 1.9 m the same as the entry hole of the auger machine. Again, the verification of web pillar widths was between 0.5 m to 4 m with the interval of 0.5 m. Then diagram showing about the strengths of different web pillar widths for the auger diameter of 1.9 m is illustrated in Figure 4-5.

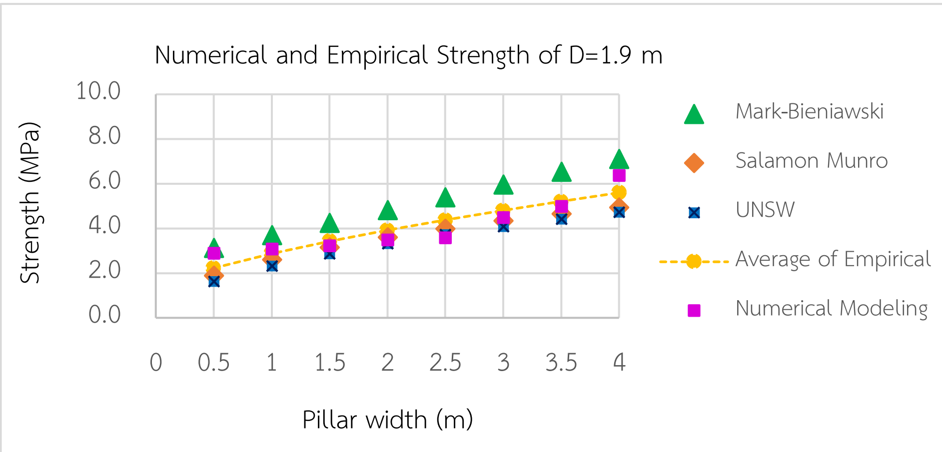


Figure 4-14: The comparison of numerical and empirical strength

In terms of strength, Mark-Bieniawski's strength gave the highest one and followed by the average strength of the three equations. Therefore, the strength of the computational model were not linear increases or decreases compared to the average strength curve of the three equations. At the beginning, the numerical strength was located upper the average strength line, then it was beneath the line. The numerical strength was located upper the average line again (Figure 4-15).

4.5.2.3 Comparison between numerical and empirical safety factor

After obtaining the stress and strength of the pillar, the safety factor can be estimated as depicted in Figure 4-16 of the empirical result and Figure 4-17 as the result of the numerical simulation.

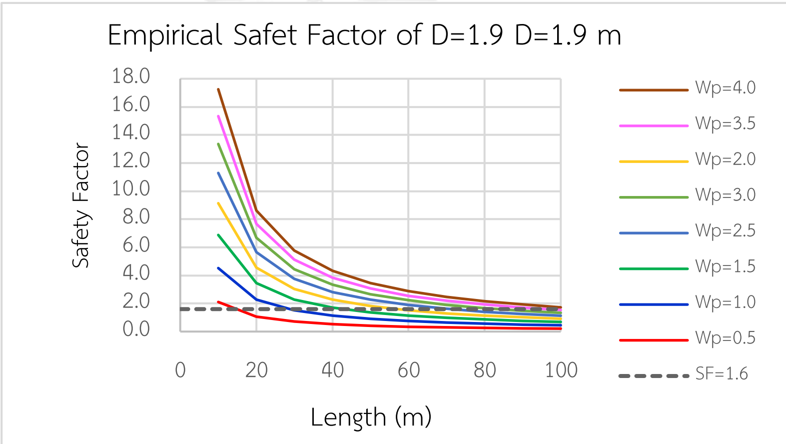


Figure 4-15: Safety Factor from Empirical Analyses for auger diameter of 1.9 m

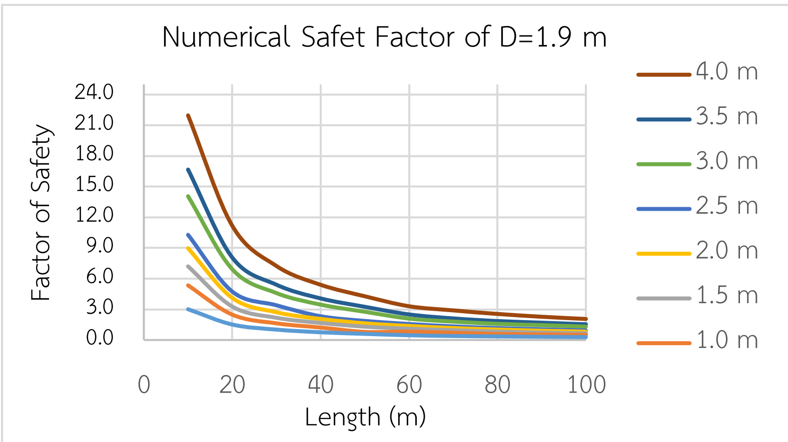


Figure 4-16: Safety Factor from Numerical Analyses for auger diameter of 1.9 m

From the results of stress and strength, the factor of safety can be calculated by these two factors' ratio. The safety factor of the empirical method is the ratio of strength to stress from the empirical while the factor of safety of the numerical analysis is its ratio of strength to stress. It is very important in the judgment of the stability of this highwall system. Based on these two analyses, the overall safety factor from the numerical analysis was almost larger than from the empirical. This can be claimed that the minimum results of safety factor were urged in the application to design this auger highwall with the drilling diameter of 1.9 m of this single pass.

4.5.3 Case of diameter of 2.1 m

4.5.3.1 Comparison between numerical and Empirical Stress

Similar to two previous two sections, 80 cases of stress including 8 cases of strength were analyzed. After ending up with the safety factor, these results are presented in this part. Figure 4-18 and 4-19 are the stresses resulting from the empirical and numerical analyses respectively.

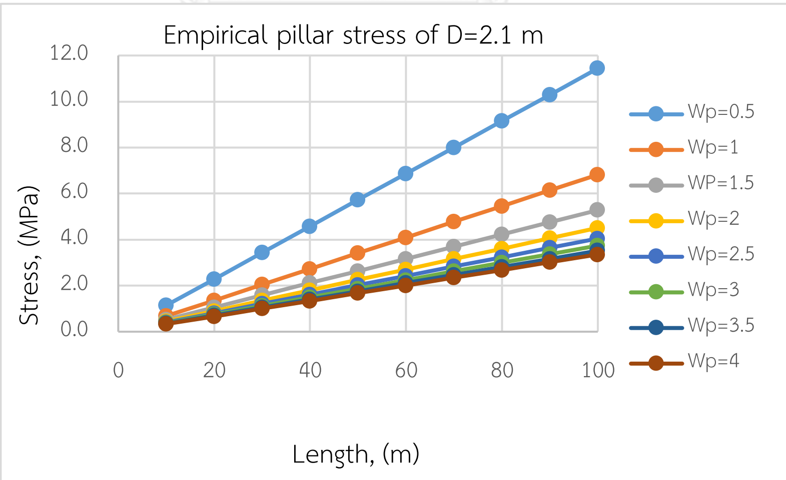


Figure 4-17: The empirical stress analyses for auger diameter of 2.1 m

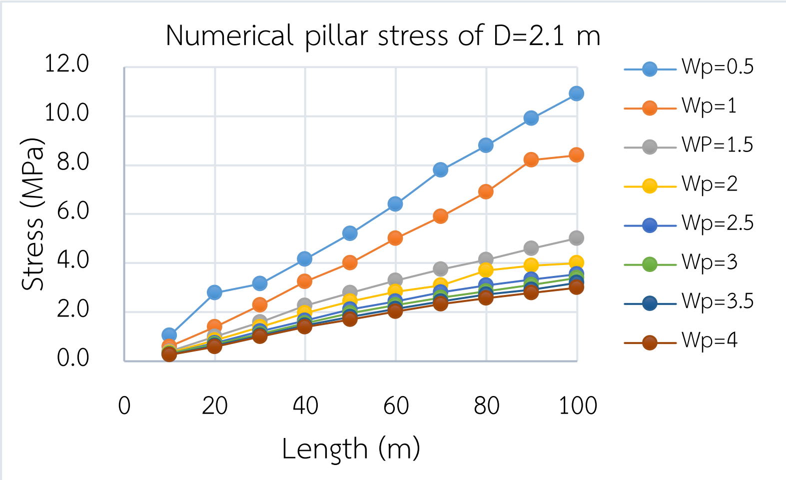


Figure 4-18: The numerical stress analyses for auger diameter of 2.1 m

4.5.3.2 Comparison between numerical and empirical strength

The strength of the web pillars for the auger diameter of 2.1 m was analyzed and made the comparison as shown as in Figure 4-20.

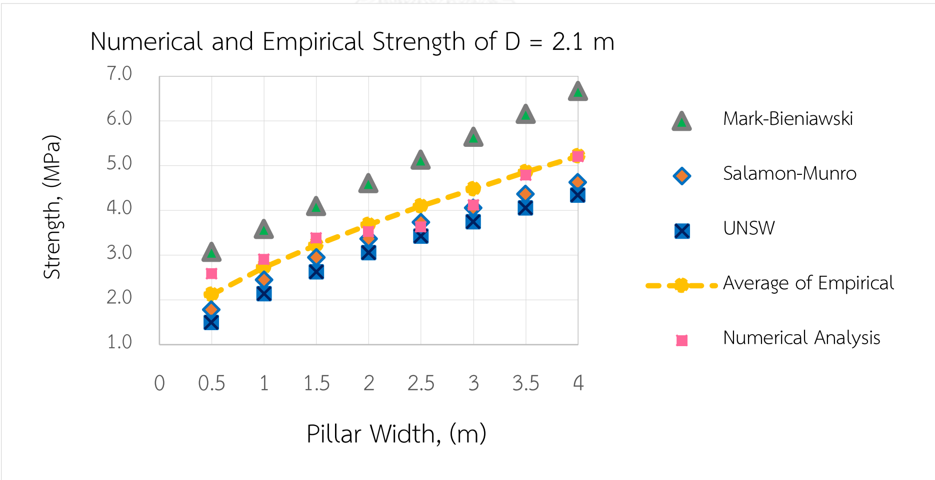


Figure 4-19: The comparison of numerical and empirical strength for the auger diameter of 2.1 m.

4.5.3.3 Comparison between numerical and empirical safety factor

The factor of safety of the auger diameter of 2.1 m for all web pillar widths was estimated from the results of stress and strength. Figure 4-21 is demonstrated the safety factor from empirical analysis and Figure 4-22 is the graph of safety factor from numerical analysis. Of the auger diameter of 2.1 m

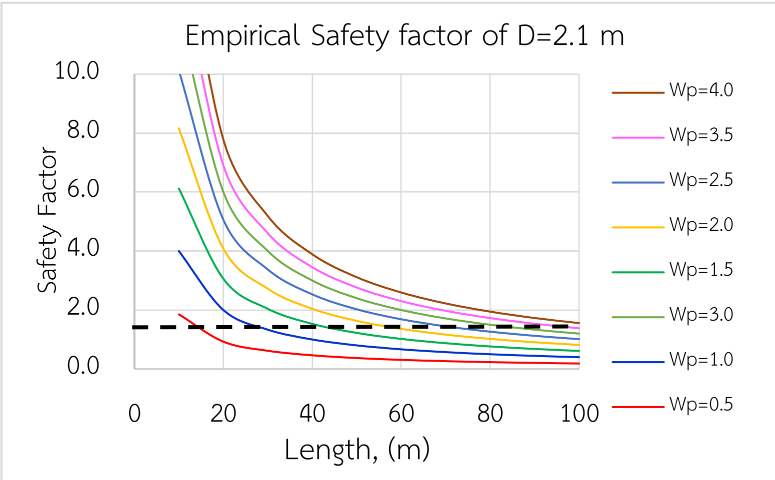


Figure 4-20: Safety Factor from Empirical Analyses for auger diameter of 2.1 m.

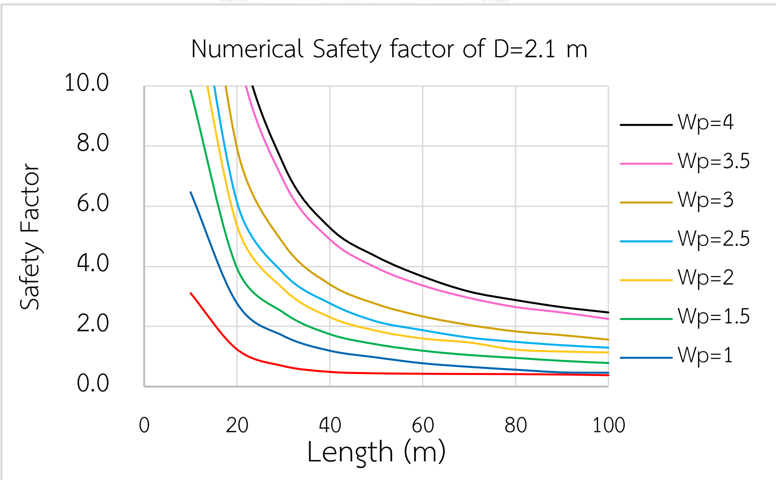


Figure 4-21: Safety Factor from Empirical Analyses for auger diameter of 2.1 m.

As already mentioned in sections of the previous two auger diameters, the auger diameter of 2.1 m provided the similar results. The stress from both formulations was quite the same Figure 4-18 and 4-19, as well as the strength which is exactly closed to the curve of the average strength (Figure 4-20). Finally, the pillar's safety factor can be solved. The safety factor from the numerical analysis was found to be larger than that from the empirical analysis for almost the cases.

4.5.4 Safe entry length

The minimum safety factor was set up to be 1.6 for web pillar design (responding to the Table. 3-2 of the single pass design). From this baseline value, the safe entry lengths can be estimated according to each pillar width. From *Figure 4-11, 4-16 and 4-22,* the maximum safe excavated length of each auger diameter can be established as presented in *Figure. 4-23.* The x-direction shows the pillar width and the y-direction as the possible drilling length. The safe drilling lengths can be increased longer if the web pillar widths are wider. The auger diameter of 1.9 m and 2.1 m required the pillar width of 4 m to drill until 100 m while the auger diameter of 1.5 m can be accessed to 100 m with the pillar width of 3.0 m.

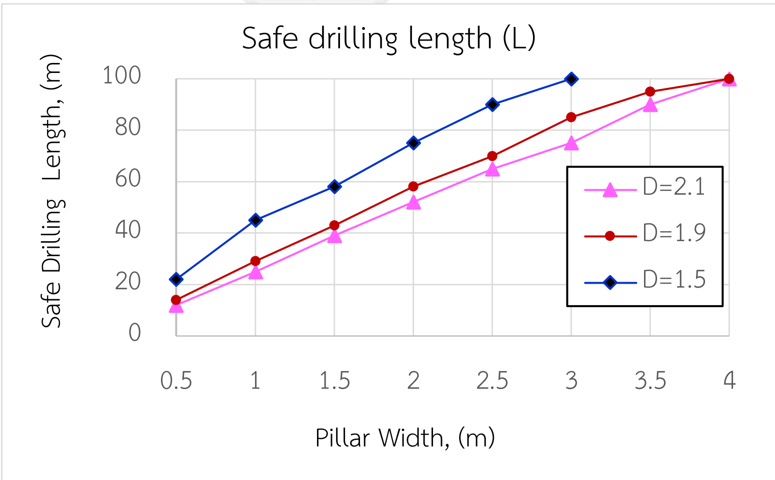


Figure 4-22: The safe drilling length

4.5.5 Coal production

The recovery ratio and tonnage of coal per excavated hole were investigated. Coal recovery ratio is higher at the shallow extracted length and gets lower on the deeper extraction length. It is opposite from coal tonnage which provides a huge amount of coal if the drilling length increased. T_1, $\%R_1$, T_2, $\%R_2$ and T_3, $\%R_3$ are referred to the percent recovery, and coal tonnage of the auger diameter of 1.5 m, 1.9 m, and 2.1 m respectively.

Figure 4-24 points out the relationship between the percent recovery and the amount of coal producing per safe drilling hole. The graph in Figure 4-24 demonstrates the contrary direction of both recovery ratio and the tonnage of coal. The increasing of recovery ratio occurred if the web pillar width was decreased, while the tonnage of coal increases if the drilling length increase. The graph in Figure 4-23 is showing the parallel connection of pillar width to the safe entry length. The bigger web pillar width, the longer safe auger hole can be drilled. So for the absolute decision for choosing one good web pillar in this design, it must be clearly examined between the recovery ratio and tonnage of coal. By plotting the safe entry length (in the y-direction) to the pillar width (in the x-direction), the auger diameters of 1.9 m and 2.1 m required the pillar width of 4 m to reach 100 meters of the safe entry length. On the other hand, the auger diameter of 1.5 m required 3 m of the pillar width to extend the length to 100 meters. This is followed the safety factor baseline of 1.6 (*Figure 4-11, 4-16 and 4-22).* Therefore, it can be determined that the smaller pillar width gave the better recovery ratio, though the shorter safe length can be mined and the less amount of coal tonnage it gets. It can be said that the highest tonnage, the longer drilling length is required. Based on Eq. 19, the tonnage of coal is really related to the safe entry length and the hole diameter. Thus:

- The greatest recovery ratio is 33% which is gained according to the auger diameter of 2.1 m and pillar width of 0.5 m. It is corresponding to 52 tons of coal obtained. After that, the recovery ratio was continued to decrease to 21%

at the pillar width of 2.0 m. The safe entry length was 52 meters with the tonnage of 225 tons a hole.

- Looking to the auger diameter of 1.9 m, the maximum recovery was 30% with the pillar width of 0.5 m but the tonnage was just only 50 tons. When the recovery decreased to 20% at the pillar width of 1.5 m, the tonnage has been increased to 161 tons.
- Since the auger diameter of 1.5 m, the maximum recovery ratio was 22% of the pillar width of 0.5 m but the tons of coal had been just 52 tons. This shows that the auger diameter of 1.5 m provided the minimum tons of coal.

Based on the description above, the better condition was the auger diameter of 2.1 m with the pillar width of 2.0 m as well as the safe entry length about 60 m. The production of coal from this was the recovery of 21% and the amount of coal mined about 225 tons per hole.

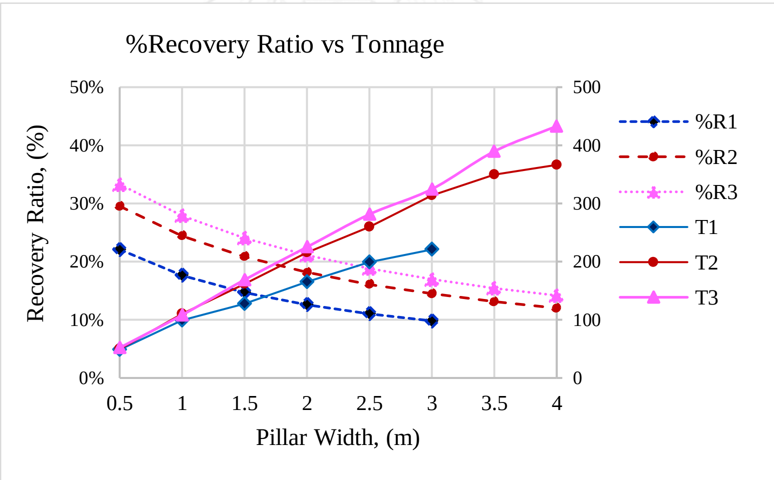


Figure 4-23: Coal recovery versus tonnage with different suggested web pillar widths

4.5.6 Barrier pillar design

In this section, the barrier pillar was studied. The relationship of the barrier pillar to the number of web pillars in a panel is the main factor to design. From the earlier results of web pillar design, the optimal design are the auger diameter of 2.1 m and web pillar width of 2.0 m with the safe drilling length of about 60 m. Then the different number web pillars in a panel of 1, 2 and 3 were proposed to design. The same concepts of web pillar design, empirical and numerical analyses were suggested in this design. Nine cases of empirical and numerical analysis were investigated to find out one best barrier pillar and the number of web pillar per panel.

4.5.5.1 Comparison between numerical and empirical stress

Both numerical and empirical stresses analyses were carried out for the barrier pillar 0f 3 m, 4 m, and 5 m. Figure 4-25 and Figure 4-26 are the demonstrations of the empirical and numerical stress of the barrier pillar widths of 3 m. For the barrier pillar width of 4 m, the stress from the empirical equation is in Figure 4-27 and Figure 4-28 is the stress from numerical analysis. The last, Figure 4-29 and 4-30 are the stresses from the empirical and numerical modeling of the barrier pillar width of 5 m respectively.

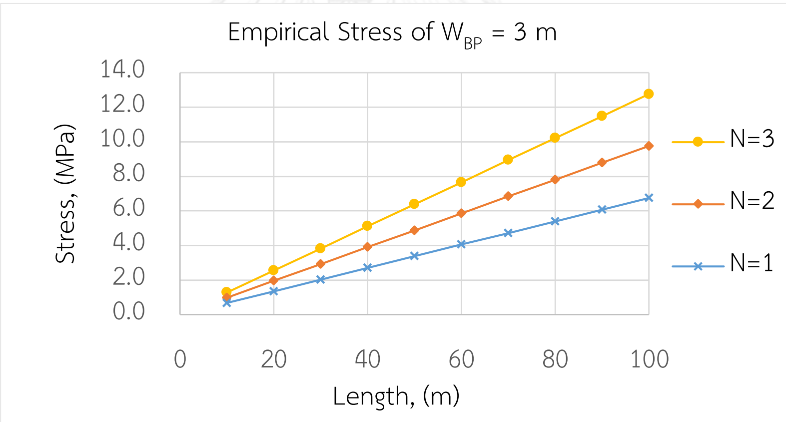


Figure 4-24: The empirical stress analysis for W_{BP}=3 m

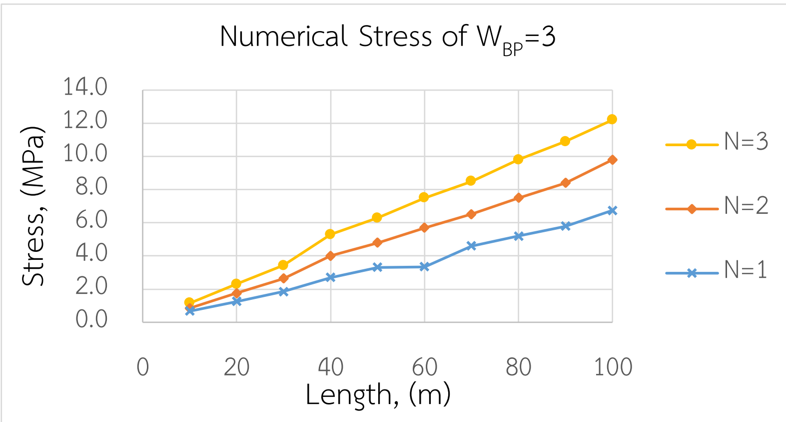


Figure 4-25: The numerical stress analyses for W_{BP}=3 m

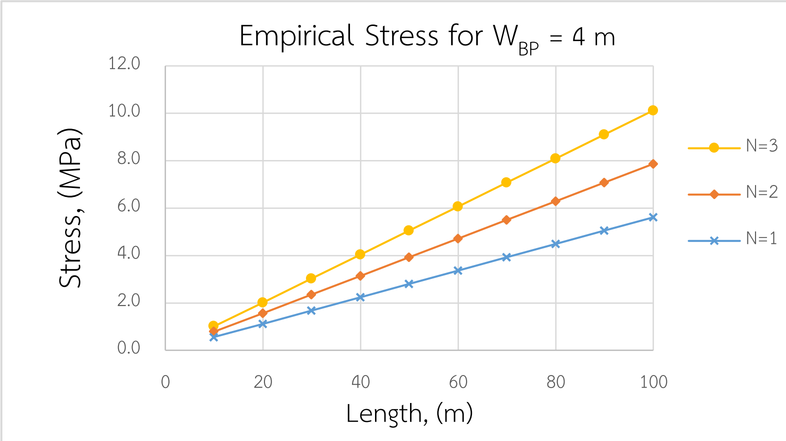


Figure 4-26: The empirical stress analyses of W_{BP}=4 m

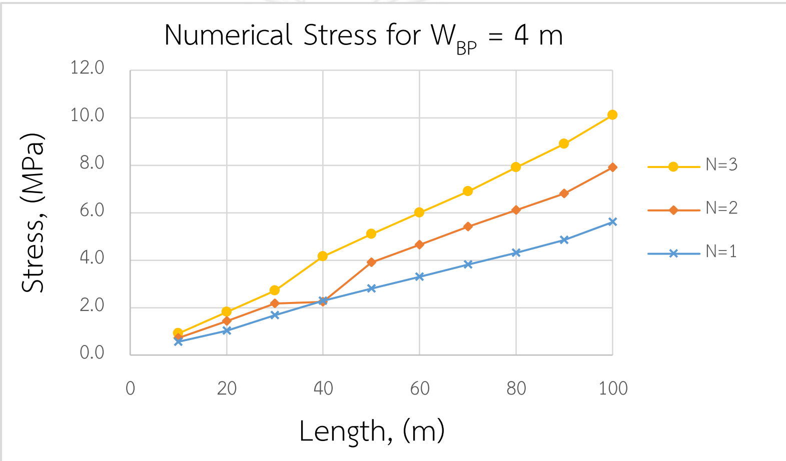


Figure 4-27: The numerical stress analyses of W_{BP}=4 m

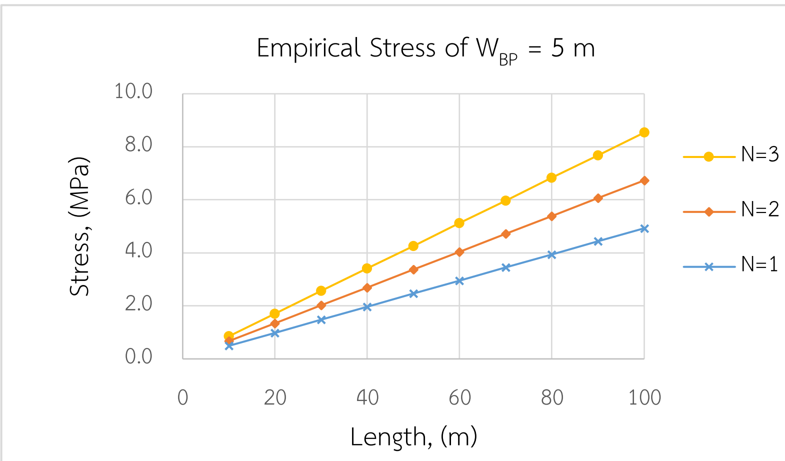


Figure 4-28: The empirical stress analyses for W_{BP}=5 m

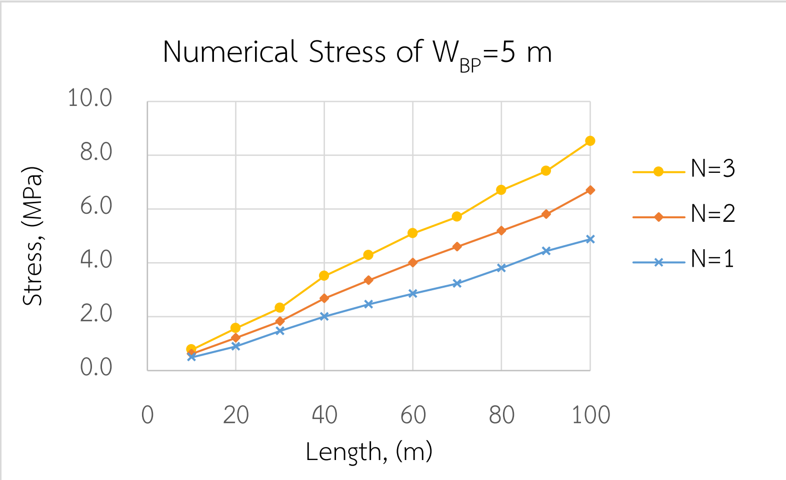


Figure 4-29: The numerical stress analyses for W_{BP}=5 m

4.5.5.2 Comparison between numerical and empirical strength

The barrier pillar strength was observed from the numerical and empirical as shown in Figure 4-31 below. The barrier pillar widths of 3 m, 4 m, and 5 m were conducted for these analyses.

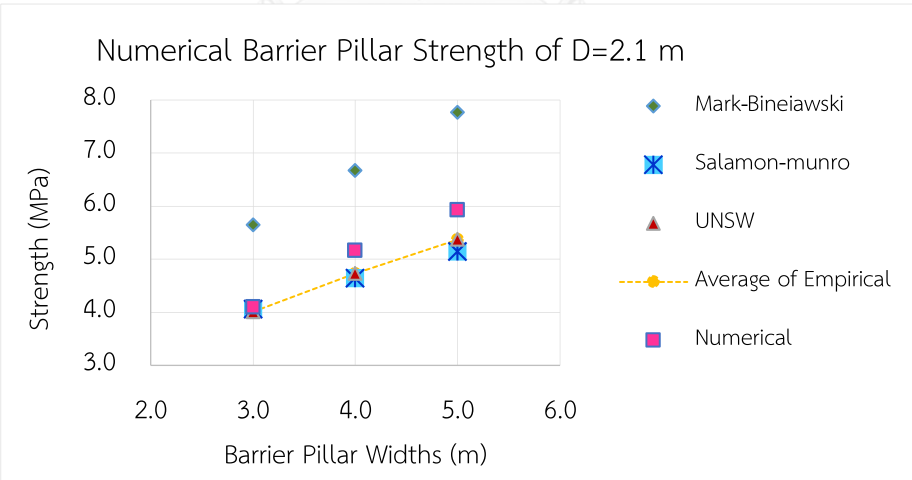


Figure 4-30: Comparison of barrier pillar strength from empirical and numerical analyses

4.5.5.3 Comparison between numerical and empirical factor of safety

Next, 3 safety factor graphs of the barrier pillar of 3 m, 4 m, and 5 m were pictured. The couple Figure 4-32 and 4-33 are the results from the empirical and numerical simulations. Figure 4-34 and 4-35 are the safety factors from the empirical and numerical results of the barrier pillar of 4 m. Last, the factor of safety of barrier pillar width of 5 m are demonstrated in Figure 4-36 and 4-37 ordinary.

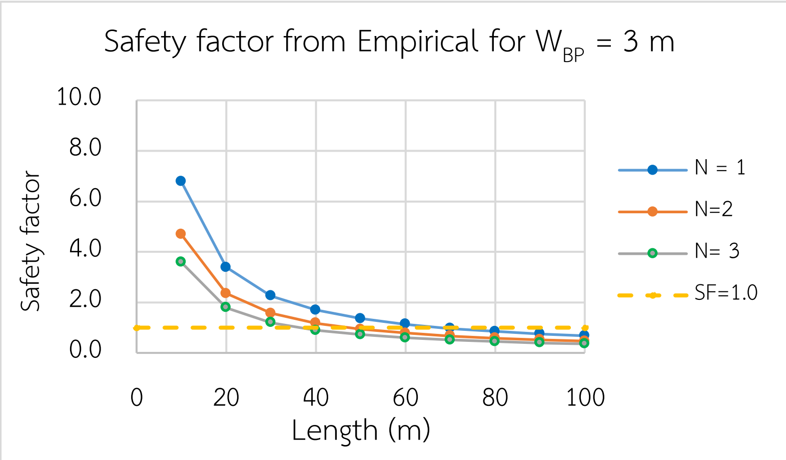


Figure 4-31: The empirical safety factor of W_{BP}=3 m

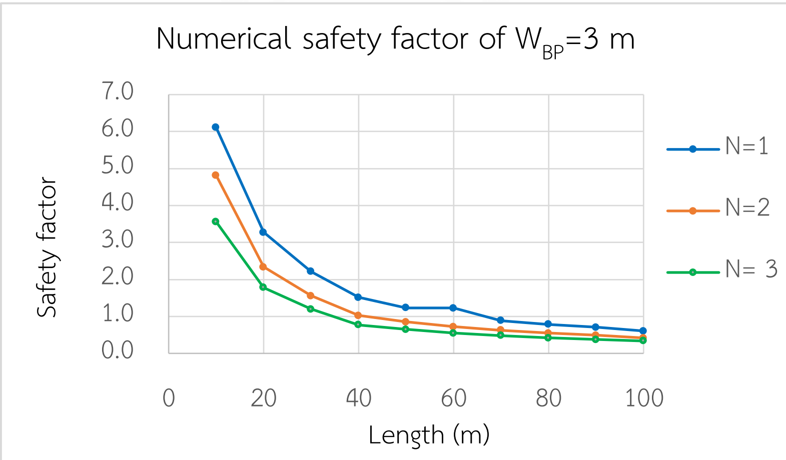


Figure 4-32: The numerical safety factor of W_{BP}=3 m

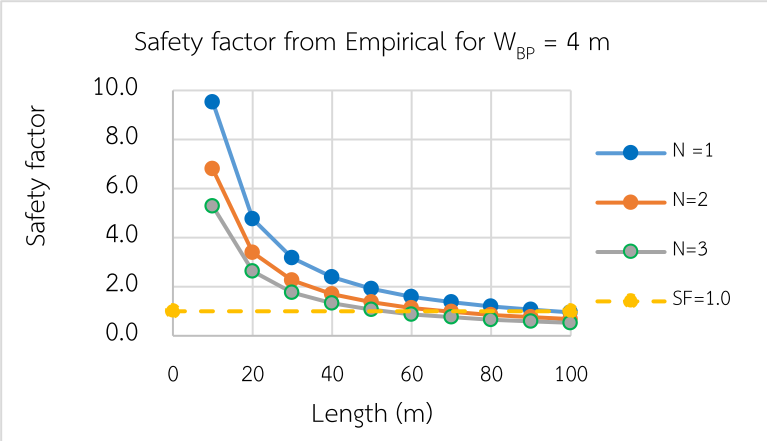


Figure 4-33: The empirical safety factor for W_{BP}=4 m

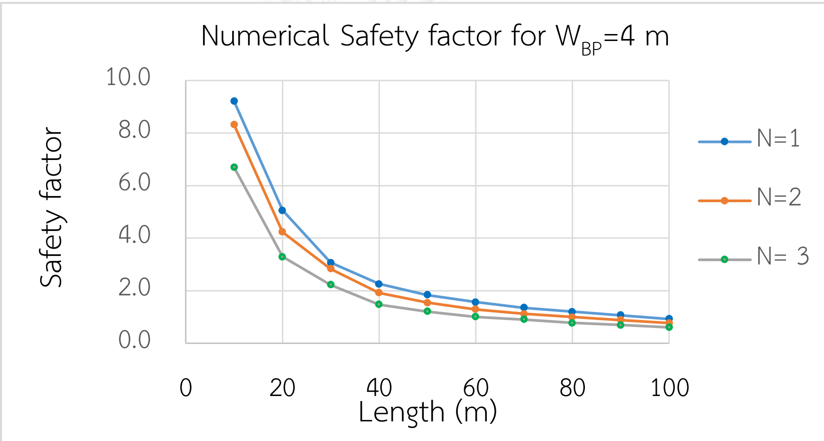


Figure 4-34: The numerical safety factor for W_{BP}=4 m

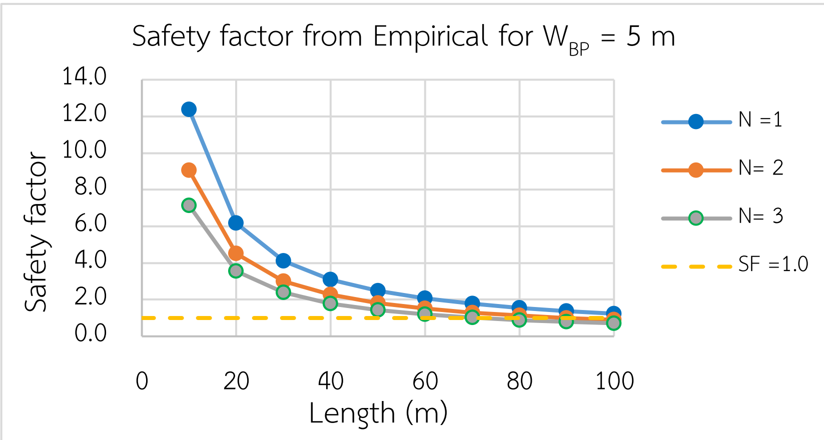


Figure 4-35: The empirical safety factor for W_{BP}=5 m

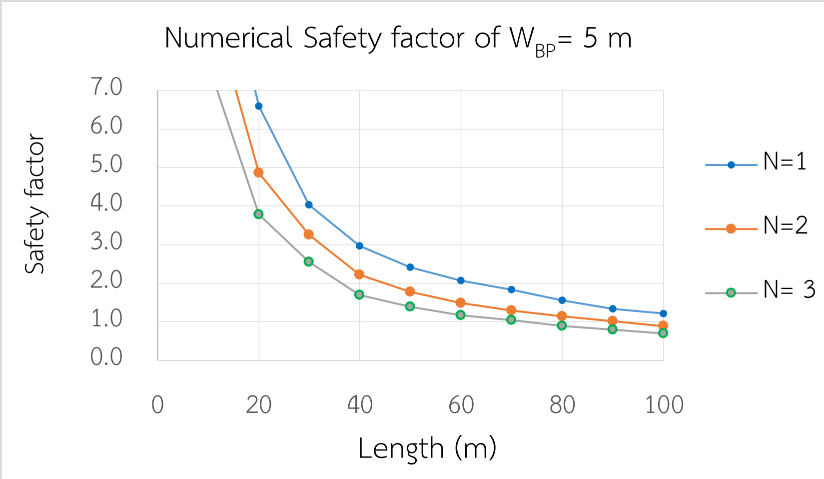


Figure 4-36: The numerical safety factor for W_{BP}=5 m

Regarding *Figure 4-25 to 4-30,* both stresses from computer modeling and empirical calculation provided the similar results. In most cases, the values of stress from the numerical modeling was smaller than those from the equations. Therefore, the numerical strength was slightly shift up than the appropriated average strength of the theories (Figure 4-31). From the stress-strength relationship, the safety factor can be carried out. Figure 4-32 to 4-37 are representing the safety factors from both analyses. Depending on this judgment, the factor of safety from average empirical analysis can be used directly to apply for Mae Tan coal. The baselines of 1.0 are drawn in each empirical safety graphs.

4.5.7 Panel design for single pass design

There is the relationship between the amount of coal mined and the number of web pillar in a panel and barrier pillar width. Every coal mine has its exact volume of the reserve. For Mae Tan mine, the total coal length of the reserve is 600 meters. After *Figure 4-35, 4-36 and 4-37*, the increasing of the number of web pillar intended to reduce safety factor. Be noted that the safety factor baseline of barrier pillar was 1.0. So from that, the observation was:

- *Figure* 4-32: This is a case of W_{BP}=3.0 m. From this figure, it can be investigated, in order to reach a safe length of 60 m, N=1 is required that its safety factor was on the baseline.
- *Figure 4-34:* This is the case of W_{BP}=4m. From this, to reach a safe length of 60 m, N=1 and N=2 can be used since their safety factor were on the baseline.
- *Figure 4-36:* This case of W_{BP}=5m show that N=1, N=2, and N=3 provided the safety factor which weas larger than the baseline in order to drill until 60m.

One more factor was included in the decision of panel design. It was the relationship of tonnage to the number of web pillar. *Figure 4-38* below is clarified this relationship. The increasing of N led to increase the amount of coal could be mined. There was the limitation of N for the design as already described. After that, the summary Table 4-1 was demonstrated the relationship of web pillar widths, the number of web pillar in a panel and the amount of coal can be mined. Finally, the optimum criteria for panel design were Wp =2.0 m, W_{BP} = 3.0 m with N=1.

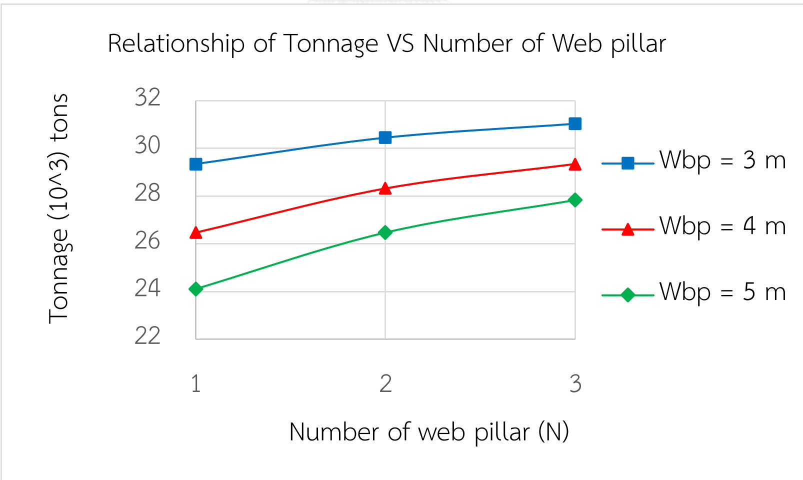


Figure 4-37: Relationship between tonnage (T), number of web pillar (N) and barrier pillar width (*W_{BP})*.

Table 4-1: Summarized table of W_{BP}, N and T.

W_{BP}	Number of Web Pillar	Tonnage (tons)
3	1	29,348
4	2	28,322
5	3	27,835

4.5.6.1 Panel Layout for Single Pass Design

The numerical stress and strength have been compared with the empirical stress and strength in this report. The numerical value of strength was smaller than Mark-Bieniawski value of strength but it was still larger than Salamon-Munro and UNSW. Furthermore, it is almost the same as the average empirical strength. The output of stresses from numerical and empirical of both web and barrier pillar were very similar to each other. So the verification of empirical analyses by numerical analysis demonstrated that the average empirical equations of Mark-Bieniawski, Salamon-Munro and UNSW should be applied at Mae Tan coal.

The safety factor of 1.6 was used to design the web pillar. Then the results showed that the auger diameter of 2.1 m, web pillar of 2 m and the minimum safe entry length about 60 m were the best selection of web pillar design with the barrier pillar of 3 m. Finally, the panel width was 6.2 m with 2 holes in a panel. The recovery ratio was obtained 21%. This is the optimum criteria for Mae Tan coal mine for a single pass design as shown in Figure 4-39.

As the recommendation, the single pass design for Mae Tan mine does not provide the best recovery and coal extraction ratio in term of economic. To increase its production, the design should be further studied in more detail and the design should be included the complicated design system as the double and multi-pass design.

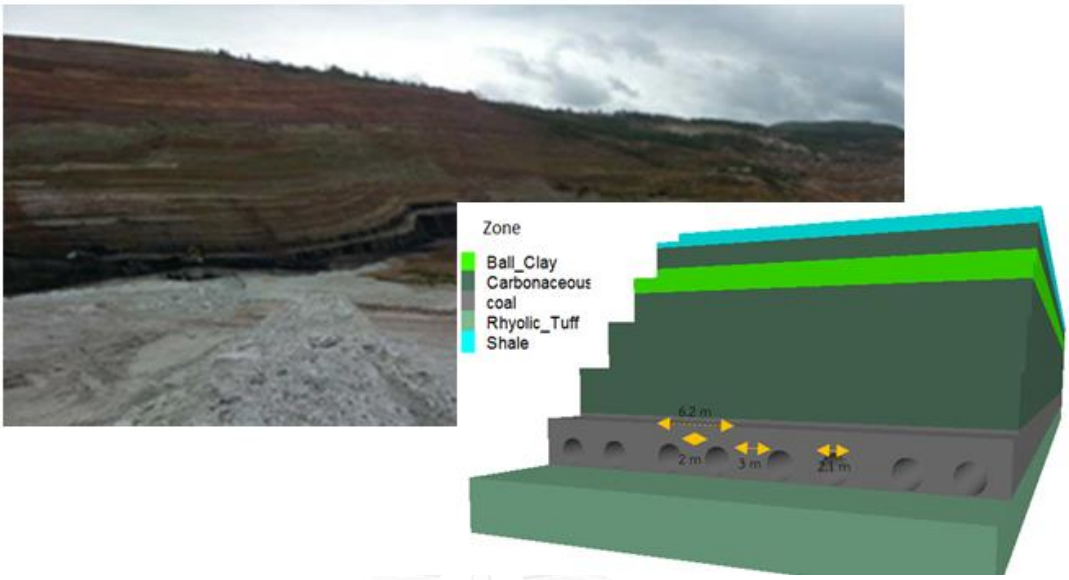


Figure 4-38: The optimum layout of the single pass for highwall system

4.6 Double passes design

The auger diameter for double passes design was only 1.5 m with the web pillar widths of 1.5 m. The observation on vertical distance between holes was 0.8 m and 1.0 m. The coal seam is 4.0 meters. When the vertical distance between holes, is 1.0 m, it means that there is no coal layer left for working as the roof support. Anyway, if the septum is 0.8 m, it is true that there is coal layer of 0.2 m helping as the roof support. The carbonaceous layer, one layer upper the coal seam, is weaker than the coal seam. Therefore, these two examinations of the septum will help to compromise this concern.

Then the pillars in the double passes will be observed in two directions: the vertical and horizontal pillar. The horizontal pillar is widened by the vertical distance between the twin holes (Figure 4-40) below is demonstrated the vertical and horizontal pillar for the double passes system.

Not only the stability of the pillars was investigated, the displacement on the top soil and the tunnel crown were also included. As the summary, the stress-strength ratio including the displacement was carried out for the final stability judgment.

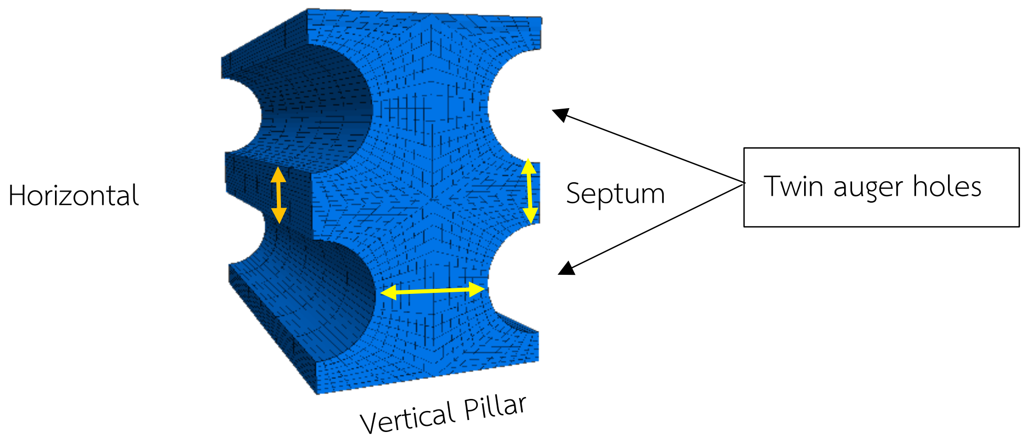


Figure 4-39: The pillar system in the double passes system

4.6.1 Double passes stress development

The stress was developed larger and larger since the depth increased. If the envelopment of stress around the hole sidewall of the tunnels connected from on to another side, it seems the pillar is in risk. The mechanism of stress expansion for the auger diameter of 1.5 m with the septum of 0.8 m is expressed in Figure 4-41.

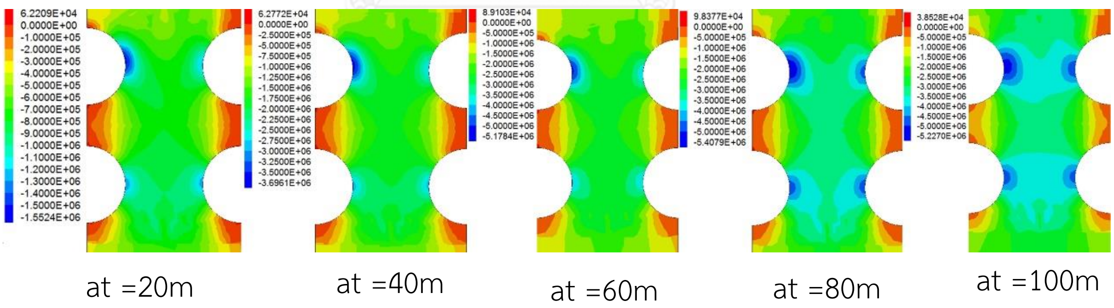


Figure 4-40: Double passes stress development around the tunnel.

4.6.2 Pillar strength in double passes

Following the concept of pillar strength estimation from the single passes, the pillar strength in double passes can be analyzed. The strength of pillar width of 1.5 m was shown in Figure 4-42. The maximum peak strength is 3.1 MPa which is further use for next calculation.

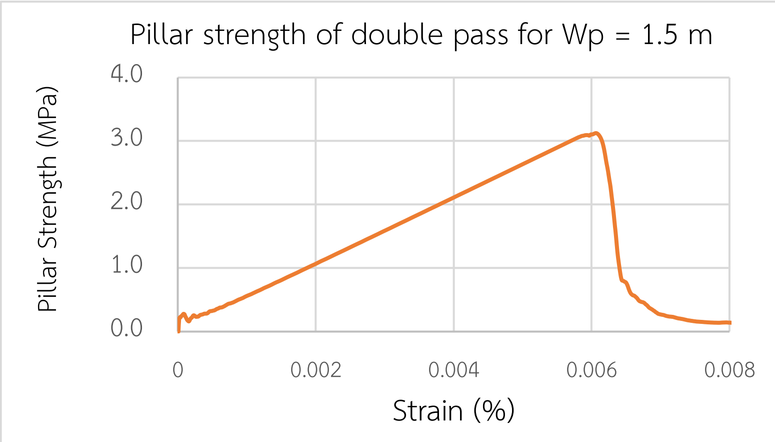


Figure 4-41: Stress-strain curve of pillar width of 1.5 m

4.6.3 Case of septum = 0.8 m

The design process for double passes is demonstrated in Table 4-2 and Figure 4-43. According to the design criteria in Table 3-4, the two safety factors were set up; 1.0 for the hole sidewall of the tunnel and 1.6 for the pillar system. In term of rock mechanics, the safety factor 1.0 is supposed to be a stable system in numerical modeling. Then the safety factor of 1.6 is the recommendation of safety value for the pillar in most cases of highwall mining. The two safety factor baselines were illustrated as discontinued lines in Figure 4.43. The stability factor of the hole sidewalls of the auger drilling holes was decreased to around 1.0 at the entry length of 50 m. the safety factor of the vertical pillar is decreased from the maximum of 4.0 from the length of 20 m to 1.4 of the length 50 m. It can be found that the horizontal pillar safety factors were always higher than the baseline of 1.6 from the beginning of the slope face to the end of the drilling length. At the entry length of 50 m, the horizontal pillar safety factor was about 3.0 which is a huge value of safety factor. As the final statement, the safe entry length for double passes of pillar width is 1.5 m and septum of 0.8 m is 50 m.

Table 4-2: The double passes design results of septum =0.8 m

L	Horizontal Pillar	Vertical Pillar	Hole sidewall	Strength	Factor of safety		
					H. Pillar	V. Pillar	Hole sidewall
20	0.4	0.8	1.4	3.1	7.9	4	2.3
40	0.8	1.8	3.1		3.7	1.7	1
50	1	2.2	3.8		3	1.4	0.8
60	1.2	2.6	4.4		2.6	1.2	0.7
80	1.5	3.1	4.9		2.1	1	0.6
100	1.7	3.5	5		1.8	0.9	0.6

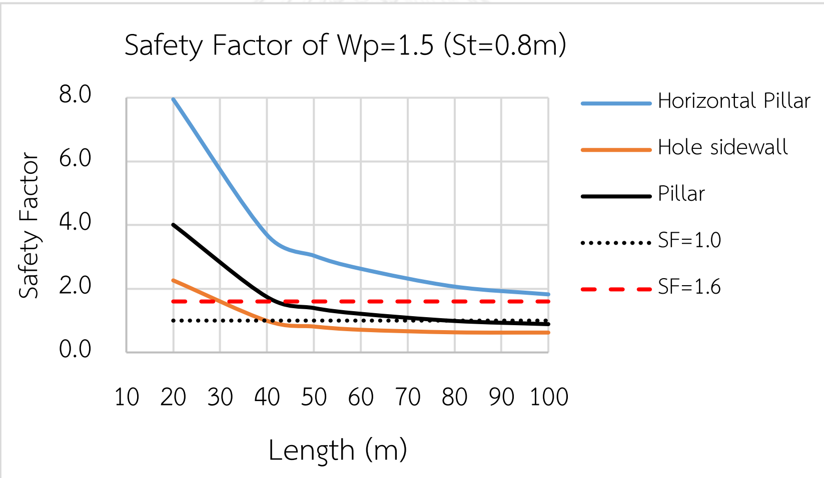


Figure 4-42: Safety factor of double passes for septum 0.8 m

4.6.4 Case of septum = 1.0 m

Similar to the septum of 0.8 m, the safety factor baselines are set up as 1.0 for the tunnels' mouths and 1.6 for both vertical and horizontal pillars. Table 4-3 is the results from the numerical analysis and Figure 4-44 is the safety factors of the three-component designs as the holes' mouths, the vertical and horizontal pillars. Referring to Figure 4-44, the tunnel gate was very weak according to the stresses concentration around the tunnels are quite high. The longest safe entry length is around 20 m with the safety factor of 1.4. Starting from the length of 30 m, the safety factor was about 0.76 downward. Not much difference, the vertical pillar safety factor is around 1.6 at the same length of 30 m. Nevertheless, the horizontal pillars which have a very stable condition when the vertical distance was increased to 1.0 m. The stability condition is better than the vertical distance of 0.8 m. In contrary, the vertical pillar and the hole sidewalls of the tunnels were not strength enough to be able to access the safe entry length only 30 m.

Table 4-3: The double passes design for septum of 1.0 m

L	Horizontal	Vertical Pillar	Hole sidewall	Strength	Factor of safety		
20	0.37	0.89	2.21	3.1	8.38	3.50	1.41
40	0.67	1.54	4.08		4.63	2.02	0.76
50	0.73	1.78	4.34		4.25	1.74	0.72
60	0.78	1.86	4.46		3.97	1.67	0.70
80	0.85	2.00	4.60		3.65	1.55	0.67
100	1.08	2.89	4.75		2.87	1.07	0.65

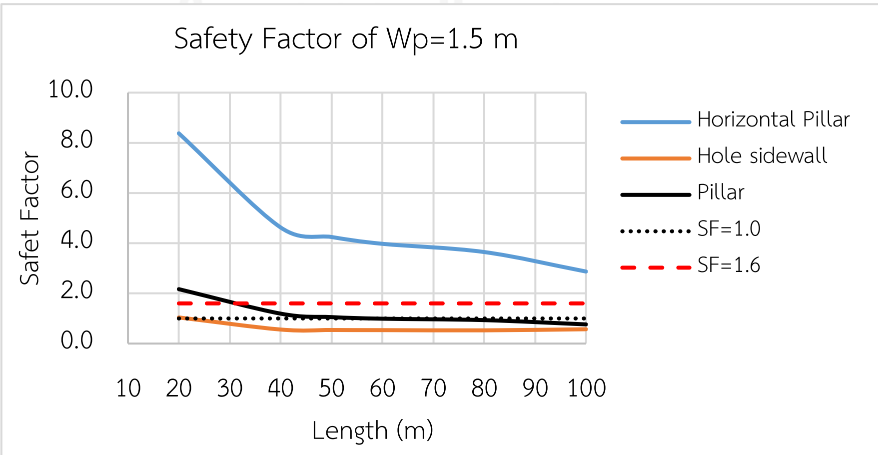


Figure 4-43: Safety factor of double passes for septum 1.0 m

As the confirmation, the two criteria of these vertical distance between holes are also one of the important factors for the design of highwall mining. The author has also included one more factor to give the evidence about the influence of the septum to the stability of the highwall system as next content.

4.6.5 Displacement

The displacement is another factor used to investigate the influence of septum to the hgihwall system. In this part, two points of the displacement were questioned to respond on the displacements; at the top of the pit (Figure 4-45) and at the crown of the upper tunnel (Figure 4-46). Be noted that *St* at the right-hand side of this figure is referred to the septum

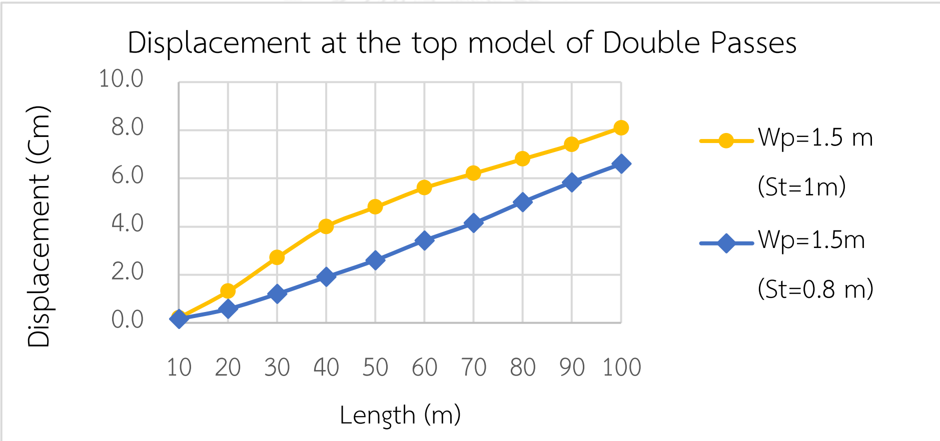


Figure 4-44: Displacement at the top of the model for double passes

Specifying on Figure 4-45, at every 10 m height at the top of the pit, the displacement increases upward for both conditions of 0.8 m and 1.0 m of the septum. Acoording to this graph, the vertical distance between holes of 1.0 m created larger displacement at the top of the pit for every observation point. However, this displacement was not much different. The maximum critical risk of the slope displacement of the open pit is 20 Cm, according to [34].

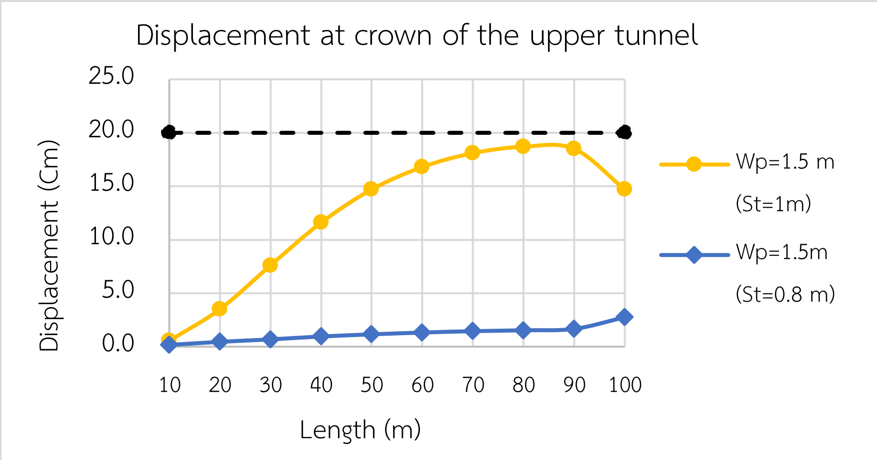


Figure 4-45: Displacement at the crown of tunnels for double passes

The same manner to the displacement on the top of the pit, the septum of 1.0 m created very high displacement at the crowns of the upper tunnels. The highest points were between the lengths of 70 m to 90 m with the highest displacement value of 19 Cm. But it started to reduce at the end of the drilling point of 100 m. This because it is already closed to the gob of the highwall where the un-drill rock is. Anyway, it almost reached the risk baseline.

For the septum of 0.8 m, the displacement of the tunnels' crowns was not so high. The maximum displacement is about 2.25 Cm. From both results of the displacements, it showed that the septum of 1.0 m provided larger displacements both at the top and the tunnels' crown. The reason behind is that one upper rock layer of the roof, carbonaceous rock strata, is not a strong roof support. Upon that, the excavation without leaving some coal as the additional support roof (in the case of septum =1.0 m) did provide the risky condition to the highwall system. In contrast, the diminution of the septum to 0.8 m which can be left 0.2 m of the coal seam on the top of the tunnels as the support created a stable roof system. The increasing of the vertical distance helped to improve the horizontal stability, however, it promotes more unstable roof system for this highwall mining.

Hence, ending up with the final reasonable agreement, the septum of 0.8 m is recommended to use in this case of double passes design of the auger diameter of

1.5 m and the coal seam of 4.0 m. The 50-meter- safe entry length is obtained from this criterion and the tonnage of coal of these twin tunnels can be estimated:

$1.25 \times 2 \times 50 \times \frac{\pi \times 1.5^2}{4} = 220 \text{ tons}$ of coal (Referring to Eq.18) and the recovery ratio from this is $\left(\frac{2 \times \pi \times 1.5^2}{4} \right) / \left((1.5 + 1.5) \times 4) \right) = 29\%$ according to Eq.19

After this, the summarized Table 4-4 is demonstrated the best study case of the double passes design for web pillar.

Table 4-4: The summarized result of web pillar design in double passes

D (m)	Wp (m)	L (m)	%R	Tons
1.5	1.5	50	29	220

4.6.6 Barrier pillar design in double passes

The web pillar collapse in the panel is the main concept used in double passes design for barrier pillar where the big room were constructed in the model. The huge model was generated with the geometry as in Figure 4-47. The twin holes were extracted by keeping some vertical distance (the same as web pillar design) as the horizontal pillar. The stress increased in the penetrated depth, when the penetrated length increase. The stress development of the barrier pillar design is demonstrated as in Figure 4-48 by cutting the cross section of the pillars for every 20 m long. The upper tunnel suffered more stress concentrated than the second lower tunnel. The barrier pillar design in the double passes system for auger diameter of 1.5 m were 1 and 2. The case studies would be representing after.

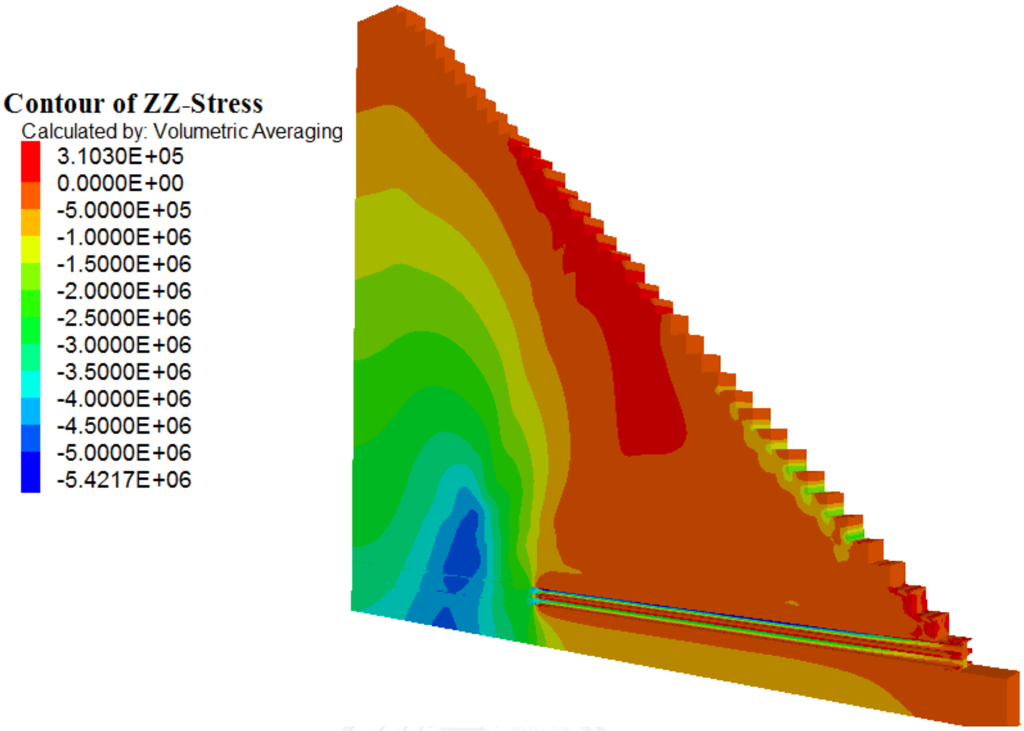


Figure 4-46: The barrier pillar generation system for double passes design

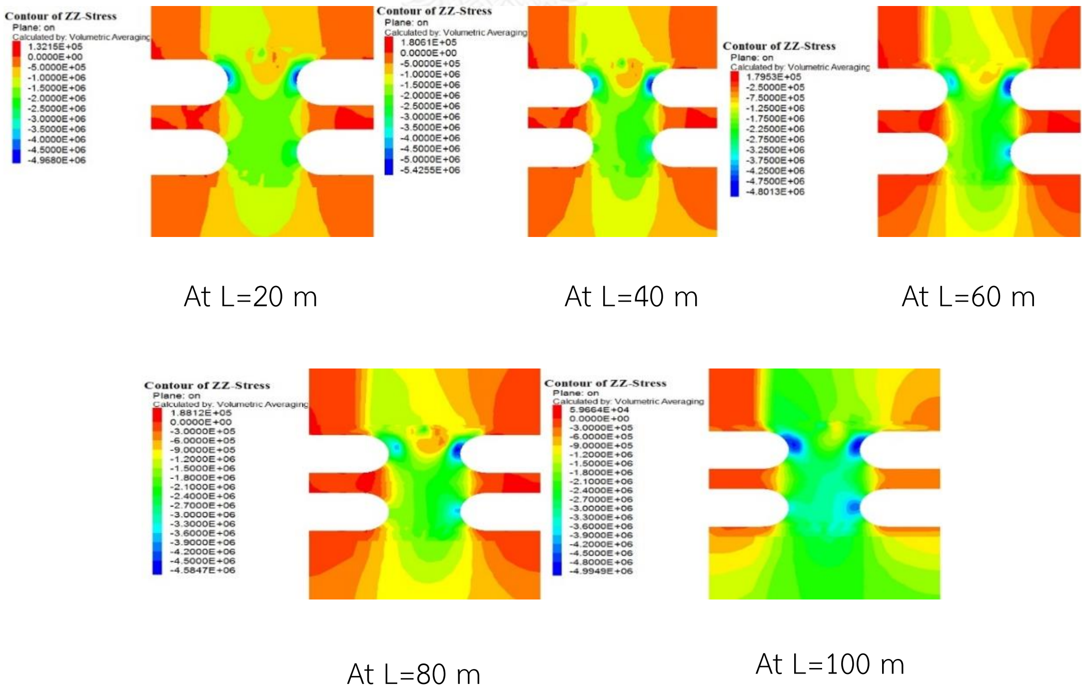


Figure 4-47: Vertical stress concentrated on the barrier pillar for double passes design for barrier pillar width of 2 m and the septum of 0.8 m

4.6.5.1 Barrier pillar design with N =1

The vertical and horizontal pillars are observed with the septum of 0.8 m as the final discussion from the web pillar design in double passes. Furthermore, the web pillar width of 1.5 m was taken to design in barrier pillar and the barrier pillar width was 2.0 m with the number of web pillar is 1. The stress data is generated from the full model of the analysis and the strength is the result of FISH function as shown in Figure 4-49 of the pillar width of 2 m in double passes system. The summarized result of the stress, strength and safety factor are proven in Table 4-5. Next, the safety factor graph in Figure 4-50.

The baseline safety factor of barrier pillar is 1.0 for the vertical and horizontal pillars and half barrier pillar's safety factor for the hole sidewall. From these two baselines, the safe entry length can be estimated. The horizontal pillar is stable until the end of the proposed excavated entry length. Following by the vertical pillar and the hole sidewall where their stabilities can be accessed to around 50-meter length. From this proof, the safe entry length of the barrier pillar width of 2 m with the number of web pillar 1 is 50 meters.

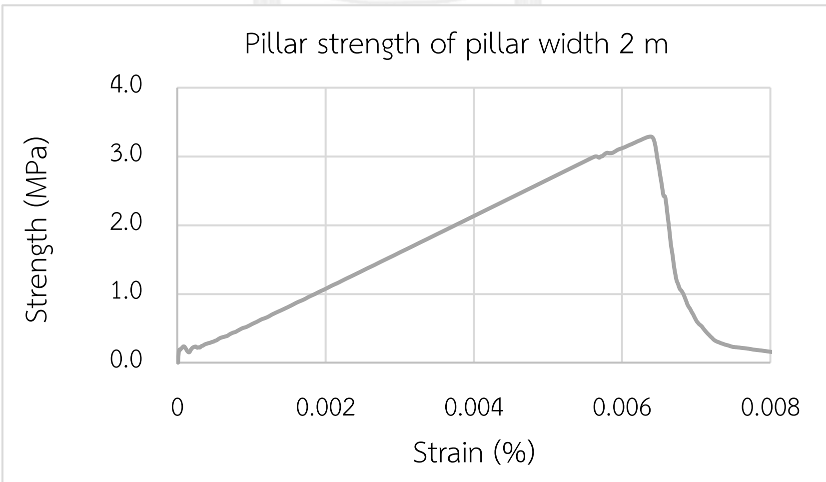


Figure 4-48: Barrier pillar strength

Table 4-5: The barrier design in double passes for N=1

N=1				Safety factor		
Horizontal Pillar	Vertical Pillar	Hole sidewall	Strength	H. pillar	V. pillar	Hole sidewall
0.35	1.16	2.49	3.3	9.43	2.84	1.33
0.80	2.59	4.49		4.13	1.27	0.73
1.00	3.13	5.40		3.30	1.05	0.61
1.15	3.70	6.25		2.87	0.89	0.53
1.60	5.13	5.80		2.06	0.64	0.57
4.00	7.30	5.84		0.83	0.45	0.57

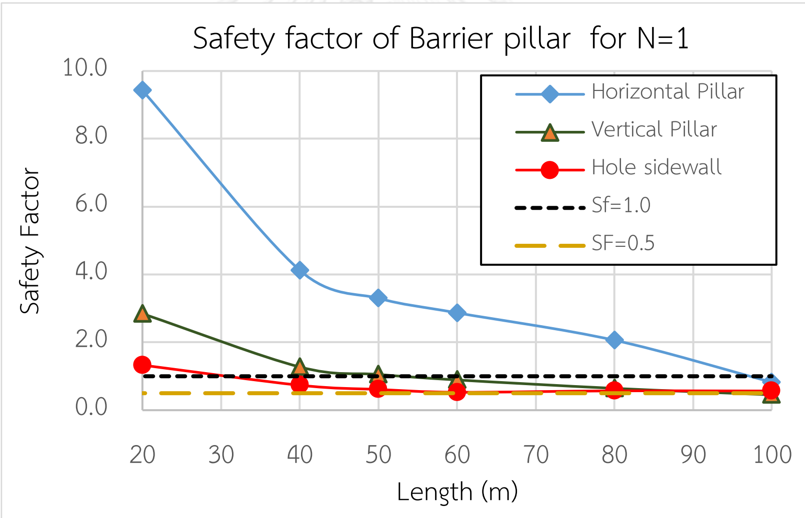


Figure 4-49: The safety factor of barrier pillar system in double passes for N=1

4.6.5.2 Barrier pillar design with N =2

The number of web pillar in a panel is 2 now and the opening is also bigger than the previous opening. The stability of the pillar is decreased since the stress loaded on the pillar is increased. The same as previous part, the baselines of the safety factors are 1.0 for both pillars and 0.5 for the hole sidewall. The result of stress and strength have been generated and shown in Table 4-6 with the plotted safety factors in Figure 4-51. From the baseline values, the safe entry length of the horizontal pillar is 60 meters while the vertical pillars are about 35 meters. The accessible safe entry length of hole sidewall is around 50 m. However, the system is followed the lowest accessible entry length which is 35 meters.

Table 4-6: The barrier design in double passes for N=2

N=2				Safety factor		
Horizontal Pillar	Vertical Pillar	Hole sidewall	Strength	H. pillar	V. pillar	Hole sidewall
0.45	4.01	2.21	3.3	7.33	0.82	1.50
1.2	6.25	4.30		2.75	0.53	0.77
1.9	6.50	5.85		1.74	0.51	0.56
3.2	6.57	6.73		1.03	0.50	0.49
4.7	5.34	8.33		0.70	0.62	0.40
5	5.70	9.80		0.66	0.58	0.34

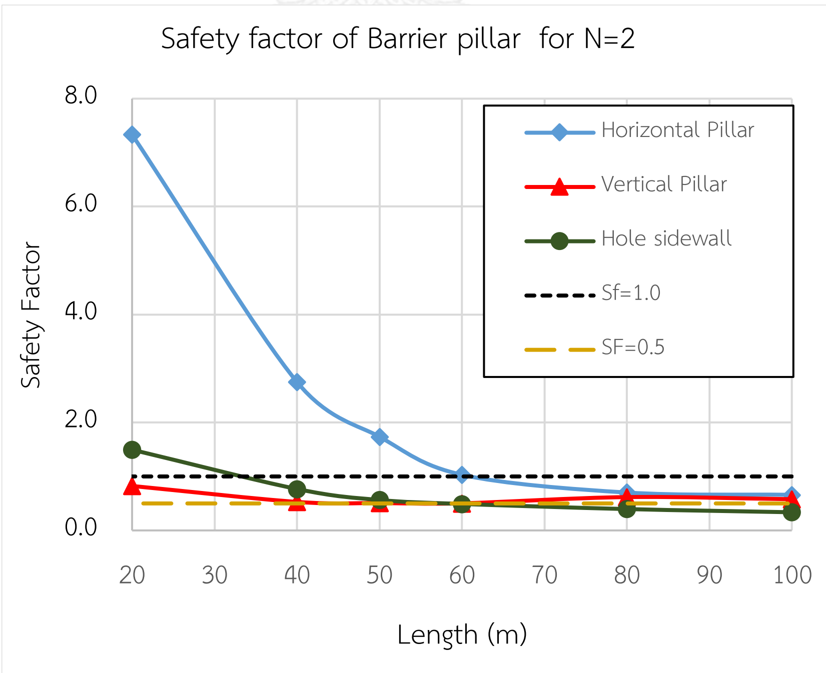


Figure 4-50: The safety factor of barrier pillar system in double passes for N=2

4.6.7 Panel design in double passes

The panel can be designed after the web and barrier pillars including the number of web pillar in a panel are obtained. From the two criteria, the optimum case is when the web pillar is 1.5 m and barrier pillar of 2.0 m with the number of web pillar is 1 and the safe entry length of 55 m. So the panel width can be designed its layout as shown in Table 4-7 as well as the amount of coal can be mined for the second coal layer of 81,295 tons. The double passes layout can be built as in Figure 4-51.

Table 4-7: coal production of the double passes of the lower seam

W_P (m)	1.5
W_{BP} (m)	2
L (m)	50
Tonnage of twin holes (Tons)	220
Total tonnage of lower seam (tons)	81,295

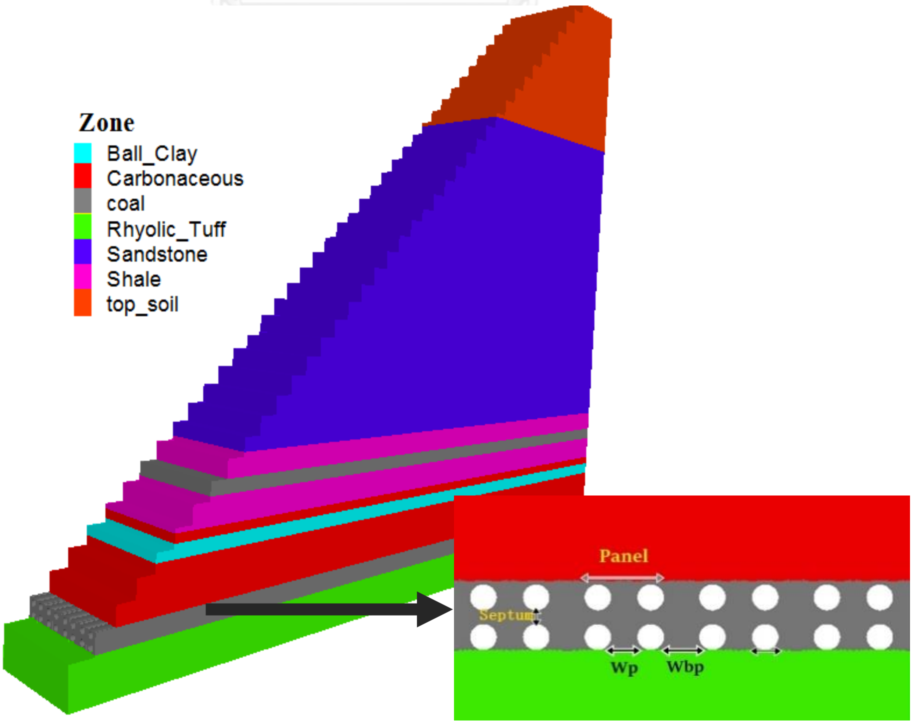


Figure 4-51: The double passes mining layout

4.7 Multiple passes design

For multi-passes design, two cases of the auger diameters were selected; the diameters of 1.5 m and 2.1 m. The multiple passes design is done on two layers of coal, the upper and lower coal seams. This design is based on the previous result which has been solved. The lower layer of coal seam will be designed with different term while the upper coal seam of 2.5-meter height can be designed only one row of entry length. For auger diameter of 1.5 m, the lower seam is designed as the double passes while the upper seam is designed as the single pass. The auger diameter of 2.1 m can be designed as the single pass for both layers of the coal seams. The separation of two auger diameter is to reduce the capital cost. Instead of spending on two sizes of the auger diameter, the company may spend only one time.

4.7.1 Case of D=1.5 m

Based on the single pass and double passes design from the previous result, for the auger diameter of 1.5 m:

- Single pass: from the single pass, the pillar width of 1.5 m can be accessed to 60-meter-safe entry length (Figure 4-11).
- Double passes: from the double passes, the pillar width of 1.5 m can be accessed to 50 m of the safe entry length with the barrier pillar width of 2 m and the number of web pillar of 1 in a panel.

So one parameter missed in the single pass design is the number of web pillar in a panel. However, from the conclusion of the single pass design, the empirical equation of stress and the average result from the strength equation can be used directly. Consequently, the panel width is designed by selecting the barrier pillar of 1.5 m and 2 m. Figure 4-53 and 4-54 are presenting the safety factors of barrier pillar widths of 1.5 and 2 m with the number of web pillar in a panel of 1, 2 and 3.

The safety factor baseline of 1.0 is again set up for the barrier pillar system. From this baseline value, the safe entry length of both barrier pillars of 1.5 m and 2 m can be estimated as shown in Table 4-8 with the different number of web pillar in a panel. After the safe entry lengths have been indicated, the amount of coal mined is demonstrated as a final judgment for the selective criteria.

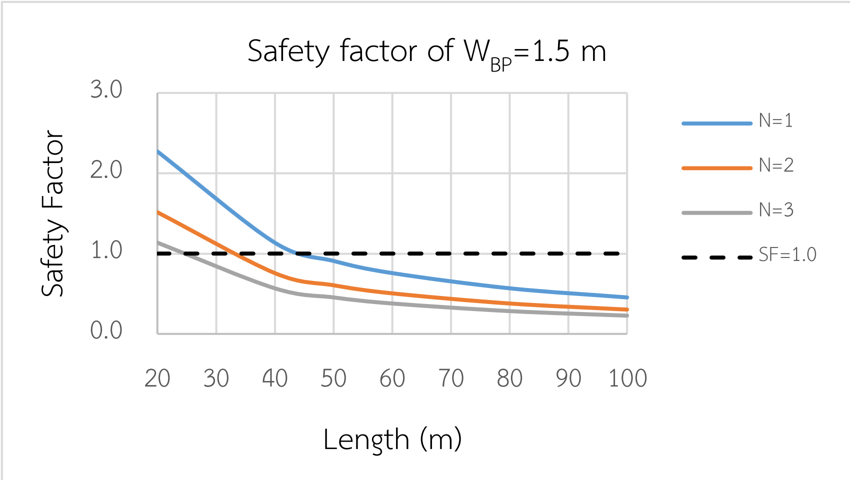


Figure 4-52: Factor of safety of barrier pillar of 1.5 m

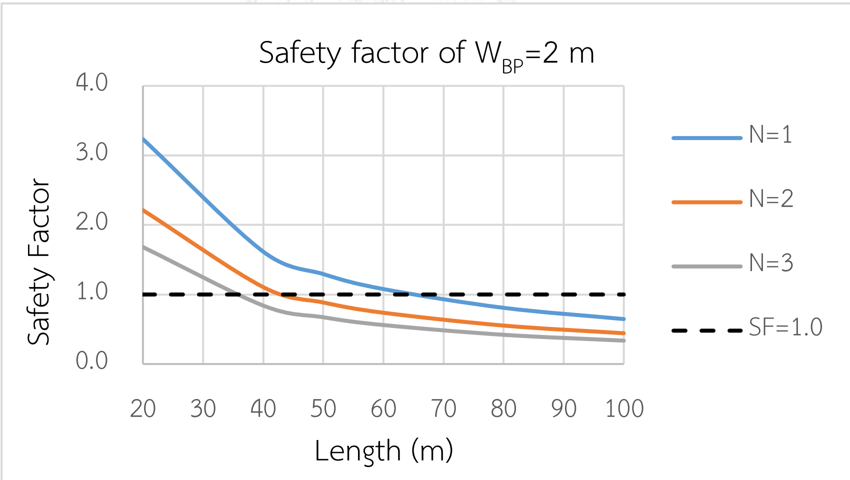


Figure 4-53: Factor of safety of barrier pillar of 2 m

Table 4-8: The summarized result of single pass design of auger diameter of 1.5 m

	W_{BP}=1.5 m			W_{BP}=2 m		
N	L	Tonnage per hole	Total Tonnage	L	Tonnage per hole	Total Tonnage
1	45	199	19880	60	133	24472
2	35	232	15463	45	99	18834
3	25	220	11045	35	77	14844

Base on Table 4-8, the best condition of single pass design for the auger diameter of 1.5 m is the web pillar of 1.5 m, the number of web pillar of 1 and the barrier pillar of 2.0 m as the same as the double passes design. This is the selective criteria for forwarding to the multi-passes design for Mae Tan coal mine.

4.7.1.1 **Highwall layout**

The design geometries of the multi-passes design can be expressed as in Table 4-9. The difference between these two passes is the accessible entry length which is 60 m and 50 m for single and double passes ordinary

Table 4-9: Multi-passes mining layout for auger diameter of 1.5 m

Seam	Design	Geometry					
		D	W_P	W_{BP}	L	N	W_{PN}
Upper	Single pass	1.5	1.5	2	60	1	4.5
Lower	Double passes	1.5	1.5	2	50	1	4.5

4.7.1.2 Coal production of multi-pass of auger diameter of 1.5 m

The coal production for the multi-passes is divided into the upper and lower coal seam production. According to Table. 4-7 and 4-8, coal of the lower and upper seams can be estimated as in Table 4-10 beneath.

Table 4-10: Coal production of Multi-passes design of D=1.5 m

Seam	Type of design	Coal Production (Ton)
Upper	Single pass	24,472
Lower	Double passes	81,295
Total		105,767

4.7.2 Case of D=2 m

Based on the single pass design from the previous result, the auger diameter of 2.1 m can be designed as the single pass. The auger diameter of 2.1 m with the pillar width of 2.0 m, it can be safely drilled for 52 m. Thus, the multiple passes design for this auger diameter will be followed this existing result. From the single pass, the optimal case of study was mentioned and the number of web pillar is 1 with the barrier pillar width of 3.0 m. Since everything is already expressed in the earlier section, the tonnage of both coal layers will be the same.

4.7.2.1 Highwall layout

The design geometries of the first and the second coal layer are the same and already expressed in Table 4-11 and the amount of coal extracted from both layer is illustrated in Table 4-12.

Table 4-11: Multi-passes mining layout for auger diameter of 2.1 m

Seam	Design	Geometry					
		D	W_P	W_{BP}	L	N	W_{PN}
Upper	Single pass	2.1	2	3	52	1	6.2
Lower	Single pass	2.1	2	3	52	1	6.2

Table 4-12: Coal production of Multi-passes design of D=2.1 m

Seam	Type of design	Coal Production (Ton)
Upper	Single pass	29348
Lower	Single pass	29348
Total		58,696

4.7.3 ***Comparison of multi-passes results***

Table 4-13 is illustrating the amount of coal can be mined from both auger diameter of 1.5 m and 2.1 m from the multiple passes technique. The auger diameter of 1.5 m provides the greater amount of coal extracted than the auger diameter of 2.1 m does almost twice. By applying the auger diameter of 2.1 m at the lower seam, the amount of coal extracted is about half of the total coal. On the other hand, with the application of this auger diameter to the upper coal seam, it can be extracted almost coal compared to the total coal in the seam. So most coal lost at the lower seam for the diameter of 2.1 m. For the double passes design at the lower seam of 4-meter thickness, almost coal can be mined from the application of the auger diameter of 1.5 m. However, coal at the upper seam is lost more due to the application of the auger diameter of 1.5 m with the coal seam of 2.5 m thick.

Table 4-13: Coal production of multiple passes

Auger diameter (m)	Total extracted coal (T)
1.5	105,767
2.1	58,696

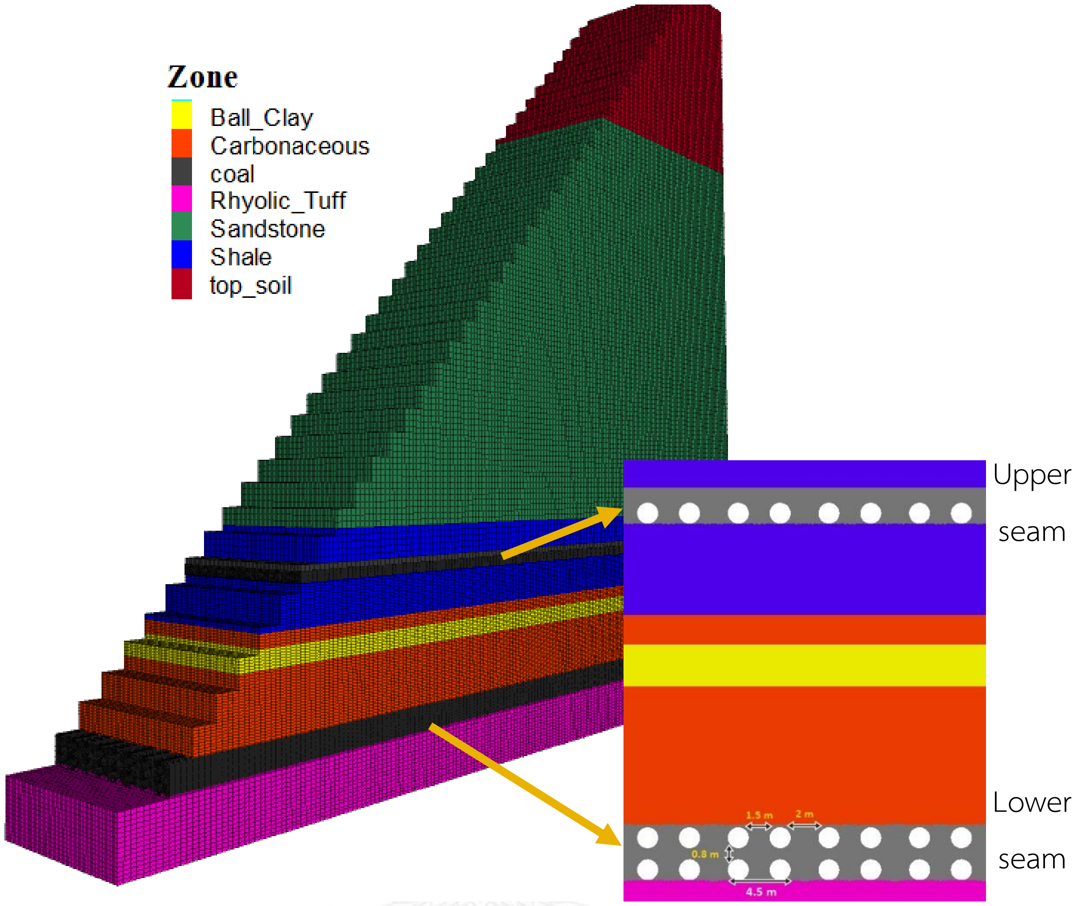


Figure 4-54: The optimum multiple-pass layout

CHAPTER 5

CONCLUSION AND RECOMENDATION

When an open pit mining is almost finished, however, there is usually some significant amount of coal remain in the highwall. Sometimes, this coal can be excavated using other mining methods. The results from the three categories of the single, double and multiple passes, the auger highwall mining can be adopted for extracting the remaining coal in the final pit of the open pit mining at Mae Tan mine. Based on the coal properties and geological condition of Mae Tan Coal Mine, the optimal designs for each category is:

- Single pass: The application of the auger diameter of 2.1 m is the best. The web pillar width of 2.0 m, barrier pillar width of 3.0 m and the number of web pillar of 1 are the most proper mining layout for this single pass. Furthermore, the amount of coal 29,348 tons can be mined.
- Double passes: The application of the auger diameter of 1.5 m with the web and barrier pillar widths of 1.5 m and 2.0 m respectively and the number of web pillars in a panel of 1 are the best mining layout for the. The amount of coal about 81,295 tons can be mined from this design technique.
- Multiple passes: The best auger diameter of 1.5 m is the best condition for the multiple passes design with the combination of the designs of the single pass at the upper coal seam and the double passes at the lower coal seam. The optimal web and barrier pillars are 1.5 m and 2.0 m respectively and the number of web pillars in a panel of 1 is the effective parameter. The amount of coal of 24,472 tons and 81,295 tons can be mined from the upper coal seam and the lower coal seam ordinarily.

In terms of resources recovery, the multiple passes with the auger diameter of 1.5 m is considered as the better choice comparing to the other design categories. Finally, it is recommended that Mae Tan mine should consider the multiple passes for extracting the remaining coal as it will provide the additional 105,767 tons of coal.

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APPENDIX

APPENDIX A

Site Investigation

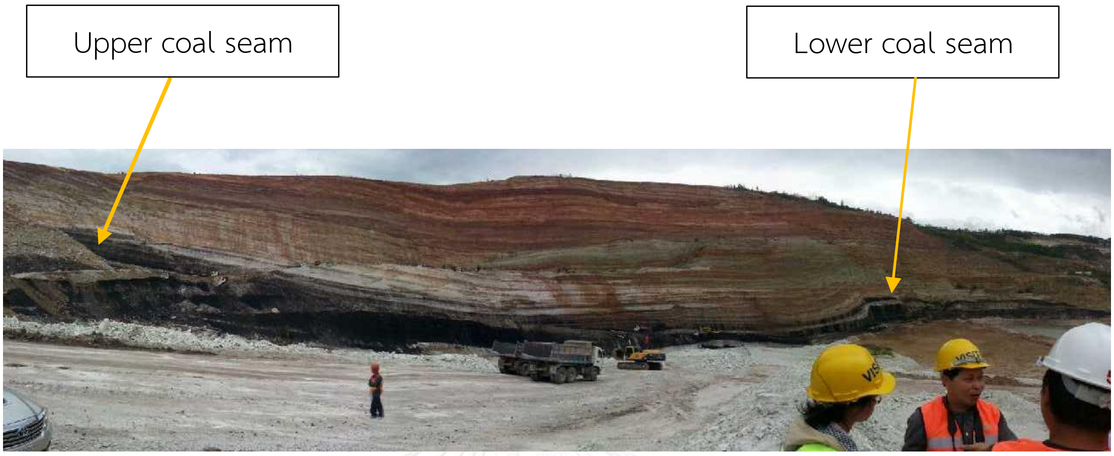

Figure A-1: Coal deposit of Mae Tan

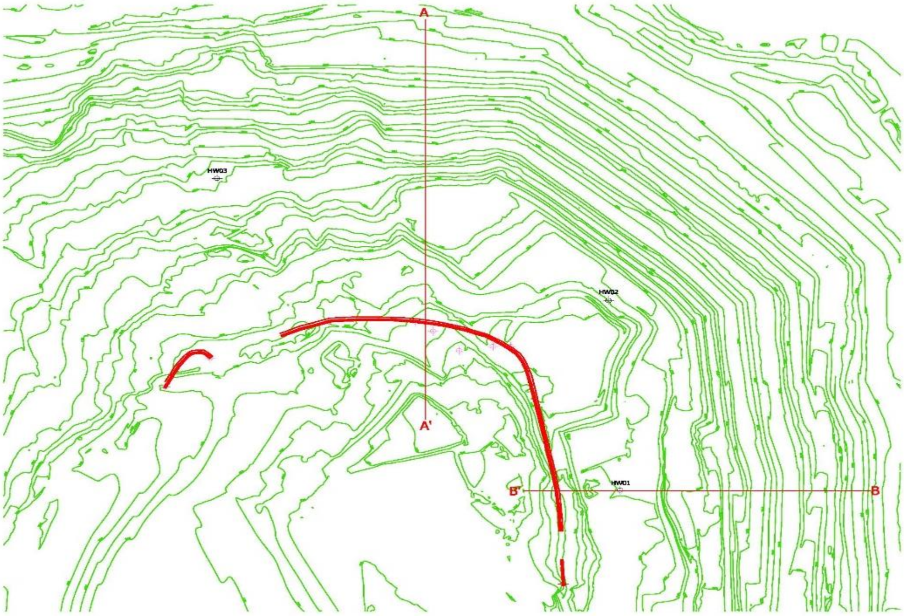

Figure A-2: Cross-sections of coal deposit of Mae Tan

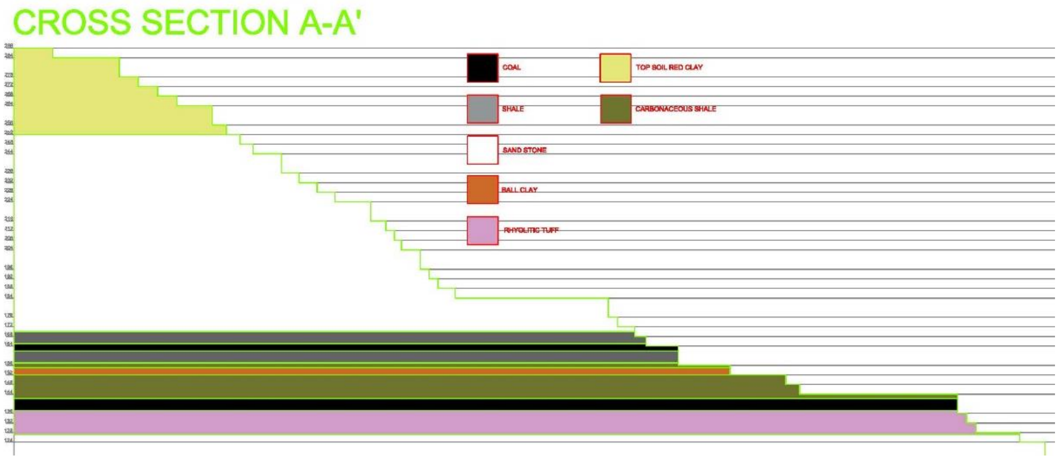

Figure A-3: Cross-section A-A’

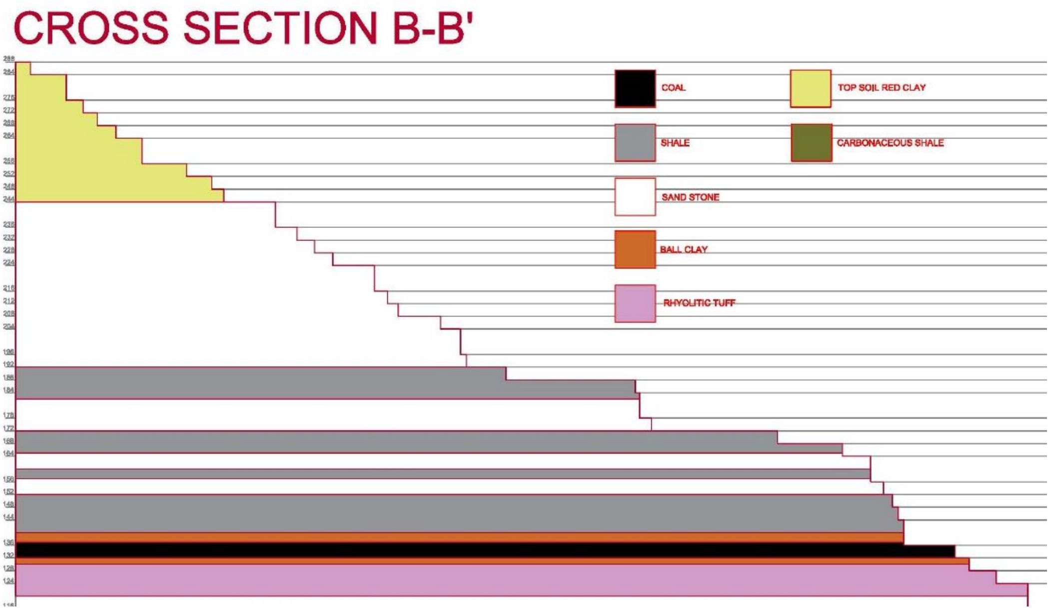

Figure A-4: Cross-section B-B’

APPENDIX B

Empirical Calculation

Table B-1: Example of empirical calculation procedure for Auger highwall Mining

H			Mark-Bieniawski		Salamon Munro		UNSW		Average
(or L)	σ_v	σ_p	S_P	SF	S_P	SF	S_P	SF	SF
10	0.22	0.88	3.28	3.73	2.23	2.53	2.00	2.27	2.84
20	0.44	1.76		1.86		1.26		1.14	1.42
30	0.66	2.64		1.24		0.84		0.76	0.95
40	0.88	3.52		0.93		0.63		0.57	0.71
50	1.1	4.4		0.75		0.51		0.45	0.57
60	1.32	5.28		0.62		0.42		0.38	0.47
70	1.54	6.16		0.53		0.36		0.32	0.41
80	1.76	7.04		0.47		0.32		0.28	0.36
90	1.98	7.92		0.41		0.28		0.25	0.32
100	2.2	8.8		0.37		0.25		0.23	0.28

APPENDIX C

Numerical Simulation

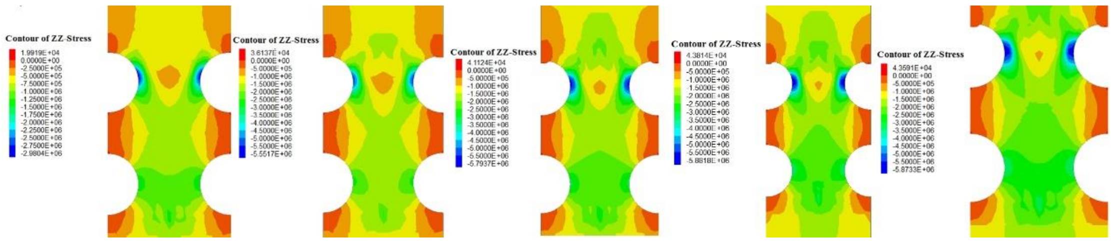

Figure C-1: The vertical stress along the pillar for Wp=1.5 m, St=1.0 m

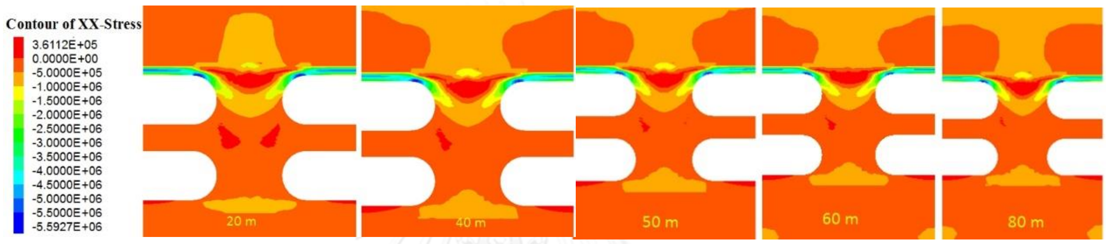

Figure C-2: The horizontal stress along the barrier pillar for the auger diameter of 1.5 m,W_{BP}=2 m, N=1 and St=0.8 m.

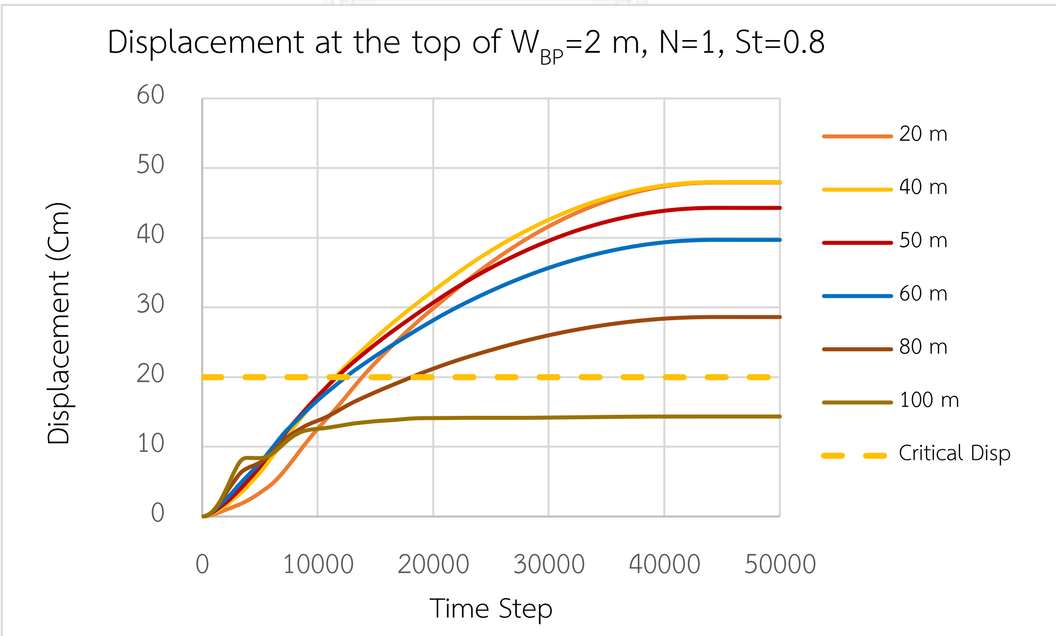

Figure C-3: The displacement at the top of W_{BP}=2 m, N=1, St=0.8

VITA

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