STABILITY CONTROL MEASURES FOR CROWN PILLAR IN CUT AND FILL UNDERGROUND GOLD MINE UNDER PROTECTED FOREST AREA, INDONESIA

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STABILITY CONTROL MEASURES FOR CROWN PILLAR IN CUT AND FILL UNDERGROUND GOLD MINE UNDER PROTECTED FOREST AREA, INDONESIA

A DOCTORAL DISSERTATION

Submitted to the Department of Earth Resources Engineering
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Abstract

When a conflict of interest between the needs to promote economic development and to preserve environmental conditions arises in the area of natural resources development such as protected forest, the underground mining method might be a solution to maximize benefit from natural resources development while keep maintaining environmental constraints. Indonesia, as one of the countries with the largest area of protected forest and mineralization found under protected forest, has permitted underground mining operations under protected forests with strict regulations. One of its strict regulations is prohibition of subsidence to occur at the surface of protected forests. To avoid subsidence, the use of the underground mining method with filling such as cut and fill is highly recommended. However, several subsidence cases in the application of this method have been recorded. The cause is collapse of stope at shallow depth during excavation. When a stope at a shallow depth collapses, failure may continue until the rock mass separates the uppermost stope with the surface, which is called the crown pillar. Increasing crown pillar thickness could be a way to prevent surface subsidence. However, part of the crown pillar in the cut and fill mining method, which is directly above the stope, is formed by an ore body. Increasing its thickness will increase its stability while also reducing mining recovery since higher volumes of ore body are left behind as a pillar. Therefore, preventing stope failure during excavation is the key to preventing subsidence as well as maintaining stability and optimizing recovery of the crown pillar. An attempt has been made to investigate stope stability in the crown pillar area of the cut and fill mining method by means of numerical simulation using Phase2 and FLAC3D software. Various countermeasures have been proposed to suit different mine conditions. The results were elaborated in six chapters as follows:

Chapter 1: This chapter gives perspective of the cut and fill mining method application in protected forests. The overview of two cut and fill variants, which are overhand and underhand, was given, stressing some points of their advantages and disadvantages. The overview was followed by the cases of subsidence at application of cut and fill as background of research. The outline and objectives of the dissertation can be found in this chapter.

Chapter 2: This chapter describes the effect of extraction of a stope in the cut and fill mining method under different mine conditions. Two different variants of cut and fill were simulated by means of numerical analysis to evaluate ground behavior and stress condition of its stope and crown pillar. It is found that the underhand cut and fill method gives a better stability condition than the overhand one. Further investigation was carried out in order to learn the stability of the stope and crown pillar at the overhand variant in different mine conditions. The results suggest that crown pillar failure is more likely to occur at cut and fill mines in the lower vein dip, wider vein width, weaker geological condition, and higher stress ratio. Moreover, the simulation of the overhand with different filling material has concluded that properties of filling material have no obvious impacts on the stability of the stope and crown pillar. The results in this chapter highlight the necessity of an appropriate support system around the stope and crown pillar, and other countermeasures in order to stabilize the stope and crown pillar in various mine conditions.

Chapter 3: This chapter reveals the effectiveness of a support system for maintaining the stability of the stope and crown pillar in different mine conditions. Two types of support systems, which are active and passive types, were simulated to stabilize the stope and crown pillar. The result shows the active type support system is not effective for supporting stopes in case the ratio of a horizontal stress to a vertical stress larger than 1.0 because the large failure zone is developed in the roof. Therefore, the passive type support should also be installed in the stopes in order to maintain the stability of stope and crown pillar if the stope is excavated at high horizontal stress conditions. In general, more supporting capacity of both types of support system is needed if the stope is excavated in more severe geological conditions, lower vein dips and wider vein widths. The direction of the active type support in the wall of the stope has an influence on crown pillar stability, especially in a hanging wall. The results of a series of numerical simulations show that rock support is proven to be effective to support stopes and also crown pillar in various mine conditions. Moreover, crown pillar recovery can be maximized by applying a combination of both passive and active type supports. However, a thick crown pillar still needs to be spared to prevent crown pillar failure that may cause subsidence.

Chapter 4: This chapter introduces the application of sill pillar as countermeasures for stability of the stopes as well as maximizing crown pillar recovery. The sill pillar can be applied by abandoning the uppermost unstable slice from the simulation of stopes supported by rock mass as a pillar. Extraction of ore will be continued above the abandoned slice. The application was simulated at several conditions where it was found that the crown pillar supported by the support system in Chapter 3 is not optimum. Results in this chapter show that the application of sill pillar is very effective to stabilize stopes as well as to increase crown pillar recovery. One of its effective utilizations is to maximize crown pillar recovery of models with a stress ratio of 2 where it can minimize a 20 m thickness of crown pillar into 5 m by leaving a 5 m thickness of sill pillar at 15-20 m in depth. The application of sill pillar not only can improve the stability of stopes but also increase the ore recovery near the surface. In general, the main purpose of the application of sill pillar is to reduce the accumulation of induced stress due to the extraction of ore affected around the stope and crown pillar. There is a possibility to optimize the sill pillar as well by reducing the sill pillar to a stope thickness ratio. However, the sill pillar may yield and the floor of the stope above it will be damaged in some cases. Monitoring during extraction of stope needs to be carried out, and if floor heave and damage is founded, remedial measures need to be taken, for example the installation of concrete in the floor. Moreover, it is also found that the sill pillar can also be extracted by applying a stronger filling material such as cement, and the recovery can be increased. After the stope above the sill pillar is filled with stronger material, the sill pillar can be extracted. However, the cost of fill needs to be considered when such a technique is applied. Therefore, this technique is acceptable only when the ore grade is relatively high. The application of sill pillar not only can improve the stability of crown pillar but also may increase ore recovery by applying the stronger filling material. Therefore, the application of sill pillar is very suitable for overhand cut and fill mines where the ore grade is not so high. Nevertheless, the application of sill pillar in mines with high grade ore will result in some portion of high grade ore left behind as a pillar.

Chapter 5: This chapter introduces the application of the grouting technique as an alternative countermeasure for stability of the crown pillar. When the ore grade is high, there will be availability to apply more expensive countermeasures to increase ore recovery. As the thickness of crown pillar decreases and the stope progressing upwards in the overhand cut and fill, the stope will be located in a shallower depth. As this condition, large subsidence due to failure of the crown pillar and large deformation around the stope can be expected. So, the application of the grounding technique was proposed in order to stabilize thinner crown pillar and control ground behavior. Since ore veins bearing gold rock mass consist of quartz, which has a small porosity, improvement by the injection of grouting material is mainly caused by infiltration of joints within vein rock mass. This effect of grout injection of rock mass properties was represented by improvement of mechanical properties of rock mass. From the results of a series of numerical simulations, it can be seen that the injection of grouting material from the surface is effective to improve the stability of crown pillar and control subsidence. As grouting material is injected into the crown pillar with a 10 m depth from the surface, the thickness of crown pillar can be decreased from 10 m to 5 m without any large subsidence, and then the ore recovery can be increased. However, the grouting method can only be applied if the ore grade is quite high and it is also allowed by the government through environmental impact analysis to inject grouting material near surfaces of protected forests. Simulation with reduction of surface grout area was carried out to investigate the possibility to minimize its impact at surfaces of protected forests. The results show that there is a possibility to reduce the grout area by giving a spacing or reducing grouting radius while the same optimum thickness of crown pillar is maintained.

Chapter 6: This chapter concludes the results of this research.

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Fukuoka, July 2016

Tri Karian

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Chapter 1
Introduction

Minimizing environmental impacts at surface area is one of the reasons to apply underground mining method for natural resources development. Nowadays, the application of surface mining is preferable to underground mining because of several reasons, varying from economic to safety issues. However, when the environmental and social constraints arise in an area of natural resources development, application of surface mining is often causing conflict of interest. Underground mining method might be a solution to maximize benefit from natural resources development while keep maintaining those constraints. Its environmental and social impacts are relatively low compared to the ones of the surface mining since its mining operation is conducted beneath the surface. Therefore, underground mining preferably to be an answer to extract natural resources at an area where conflict of interest between natural resources development and environmental protection arise.

One of the areas where conflict often arises between the needs to promote economic development through natural resources development and to preserve environmental condition is protected forest. Protected forest has an important role for environmental protection such as preventing climate change, conserving biodiversity, providing ecosystem services, preventing landslides and other major disasters (Naughton et al. 2005; Simms 2006). It is important to preserve the protected forest in order to maintain its function. However, it is often found that mineralization such as gold, silver, copper, lead, and zinc lies in the territorial of protected forest. This has caused dilemma whether to extract the valuable deposit within the protected forest or to keep it in order to preserve the function of protected forest.

Indonesia, as a country that lies within magmatic arc belt with a large protected forest area, might experience conflict of interest between natural resource development and environmental protection. Data from the Ministry of Forestry shows around 299,170 km^2 protected forest and 273,990 km^2 conservation forest areas can be found throughout Indonesia region (Indonesian Ministry of Forestry, 2014). Mineralization has been found in several protected forest of protected areas. Among those mineralization, the most well-known are gold mineralization found in Gunung Halimun Salak National Park (Basuki et al. 1994), Bukit Barisan Selatan National Park (Andrews et al. 1991), Bogani Nani Wartabone National Park (Carlile et al. 1990), and protected forest of Halmahera (Carlile et al. 1998). Currently, more mineralization in protected forest are inevitably to be found as ore exploration is still carried out by mining companies. Up until December 2013, 78 forestry permits for mineral exploration has been given by the Ministry of Forestry in Indonesia. With the potential growing number of mineralization finding in protected forest, the number of potential conflict of interest will be arise.

In order to manage natural resources development and avoid conflict of interest at protected forest, Indonesian government through Presidential Decree No. 28 year 2011 obliged mining companies which were given mine permit (IUP – Izin Usaha Pertambangan) to utilize underground mining method. An effort to keep the basic function of protected forest also described in the document by making strict requirement to obtain permit as well as monitoring and evaluating program during the mine lifetime. Surface subsidence due to underground mining activity is strictly prohibited as stated in article 10. As a consequence of this strict regulation that prohibits surface subsidence to occur at protected forest, underground mining method with filling technique is highly recommended.

The use of underground mining method with filling technique is not new in Indonesia. Several mines has been applying cut and fill mining method such as Pongkor Gold mine, Cibaliung Gold mine, and Kencana Gold mine. This method offers a long term environmental protection advantage by applying backfill material to the mined out stope. However, due to particular reasons such as inappropriate supporting method or severe geological condition, the possibility to disturb the surface still exists. Several surface subsidence cases due to application of this method have occurred in the past (Bell et al. 2000). Surface subsidence in protected forest can damage the surface and also the strata below it. This will lead to the distraction of protected forest function. Therefore, it is important to find countermeasure method to prevent that problem. As the number of cut and fill mine under protected forest increases in the near future, this study would give indirect contribution to the economic development through natural resources development and environmental preservation of protected forest.

1.1. Perspective for Cut and Fill Mining Method Application in Protected Forest

The strict regulation to preserve environmental condition during and post mining activities make the choice of underground mining method that can be applied at protected forest become limited. Based on the support that is utilized, three classes of methods are recognized i.e. unsupported method, supported method and caving method (Hartman 1987). Caving method, conduct mining by caving the ore body and country rock, will definitely not a choice. Caving method is likely to cause subsidence ranging from 10% to 80% of mine height for longwall method (Peng and Chiang 1984, 1992) to a large scale for sublevel caving or block caving method (Ward 1981; Hamrin 1982; Tobie and Julin 1982). This leaves the two other methods, which are unsupported method and supported method, as a candidate for mining under protected forest.

When both ore and country rock are competent, there is a possibility to apply unsupported method. Stope and pillar mining, shrinkage stoping, and sublevel stoping are the unsupported methods which possible to fulfill the strict regulation given by the government. However, some environmental concerns need to be considered when using this method. Pillar robbing will be restricted since it may cause surface subsidence. As for sublevel stoping, some environmental impacts need to be considered such as vibration, air blast or structural damage that may occur as the result of large blast (Mitchell 1981; Hamrin 1982; Hartman 1987; Haycock and Aelick 1992; White 1992). Other major concern when applying this method is the long term stability of the opening after mine closure. Abandoned mine working possess subsidence threat in the future as reported by several researches (Statham and Treharne 1991; Clarke et al. 2009). One of the causes is the pillar or opening failure that may occur to the pillar and abandoned mine working left in those methods. There is an option to fill the empty void in the room and pillar or shrinkage stopping. However, those two methods offer 60% - 80% ore recovery due to the need to left pillar in the operation (Morrison and Russel 1973;

Hamrin 1982; Lyman 1982; Haycocks 1992; White 1992; Haptonstall 1992). Therefore, it will raise question whether its recovery and mining scale can compensate the cost for filling.

Following the disadvantages of the other two classes, the supported method is the most suitable method to be applied in protected forest. Supported methods are those methods that require some type of backfill to provide substantial amounts of artificial support and maintain stability in the exploitation opening of the mine (Hartman 1987; Brackebusch 1992). Three methods are classified into this class which are cut and fill stoping, stull stoping and square set stoping. However, among those three methods only the cut and fill method which is widely applied in the world whereas the other two is infrequently used and relatively unimportant today (Hartman 1987).

Similarly with the other supported methods, cut and fill method needs backfill material as well as support and reinforcement to prevent instability of openings. Ore deposit is mined in a horizontal slice while the mined out slice then backfilled by using backfill material to provide additional support for the country rock surrounding the stope as can be seen in Figure 1.1. In full-mechanized operation roadway is driven from the surface and connected to the stope by using cross cuts. High ore recovery rate (90% - 100%), adaptable to mechanization, possibility to use surface waste as filling material are among advantages of this method apart from the environmental advantage that has been mentioned before (Morrison and Russel 1973; Thomas 1978; Hamrin 1982; Waterland 1982; Brackebusch 1992; Paroni 1992). Discontinuous operation due to filling operation is one of disadvantages of applying this method. Another major disadvantage is its cost which fairly expensive compared to the others due to labor extensive and, mainly, the application of backfilling. Backfilling application may take up to 20% of the total operating cost of the mine (Grice 1998). This disadvantage has limited its application on the precious deposit such as metalliferous deposit.

Eight variations of cut and fill mining method are reported (Lucas and Haycocks 1973) with two of them being the widely practiced including in Indonesia. Stoping direction is the main difference between each variation. The detail of these two variations will be described in the following sub-sections. In general, both of the variations can be applied in the protected forest, thus it is worthwhile to discuss it from economical point of view in order to determine which one is more preferable for mining company.

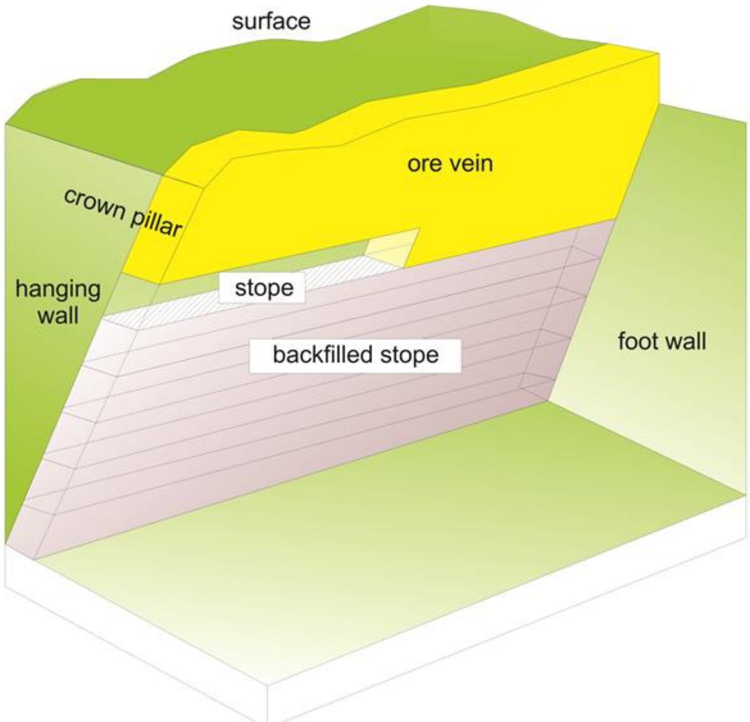

Figure 1.1. Schematic of cut and fill underground mining method.

1.1.1. Underhand cut and fill mining method

Underhand cut and fill mining method is commonly used in weak rock mass condition (Kump and Arnold 2001; Bretchel et al. 2001). In this variant, first slice is executed from the upper level progressing downward (Figure 1.2). Backfill material is inserted after the slice fully mined out. The next slice will be executed under the backfill material. The backfilling material should be strong enough to stabilize country rock as well as protecting mining operation activity at the lower level. Among the major types of backfilling material listed by Crandal (1992), cemented hydraulic fill (CHF) is commonly used in this method. Having cemented hydraulic fill offers several advantages such as providing the strongest possible fill compare to other fills, reduce rock bursting problem in deep mine, reduce dilution and improve grade control (Crandal 1992). However, it gives the highest initial cost for the preparation plant and higher cost due to cement addition. An example of cemented hydraulic fill application in Lucky Friday Mine, USA cost around 4.52 US$/ton ore mined (Peppin 2001). Such high cost will not be a burden for a company which mines a high grade deposit. In Indonesia, one of the gold mining companies named PT Nusa Halmahera Minerals applies this method to mine the ore gold with an average grade 18 gr/ton.

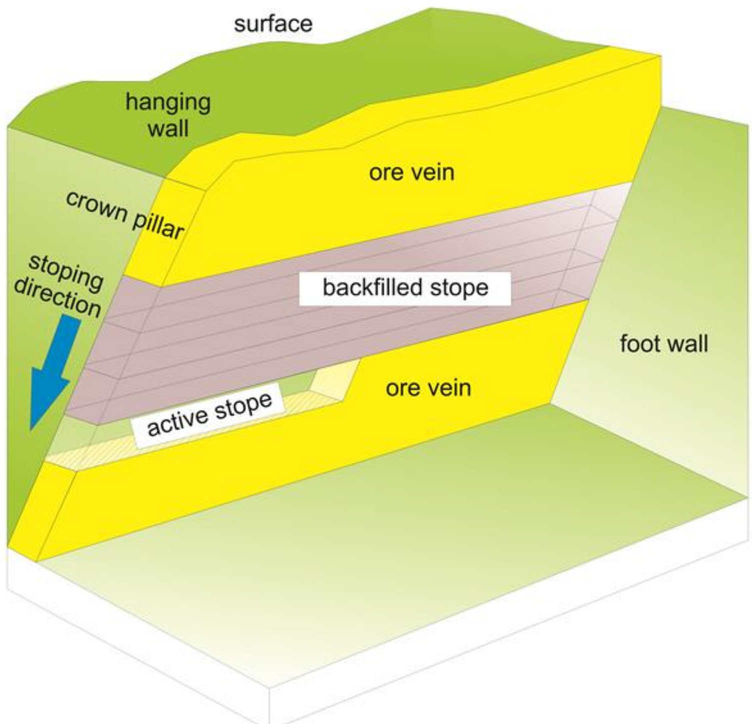

Figure 1.2. Schematic of underhand cut and fill underground mining method.

1.1.2. Overhand cut and fill mining method

When it is found that rock mass around the deposit is in good quality, overhand cut and fill mining method is preferable to be applied than underhand mining method. Application of overhand cut and fill in weak rock mass is possible but may lead to excessive need of rock support such as reported by Kump and Arnold (2001). When such case occurs, cost of rock support in weak rock may overlap the cost needed to install cemented hydraulic fill.

In contrary with the stoping direction of underhand ones, stoping is started from bottom level of the prospect. After one slice is completely mined out, backfill material is inserted not only to provide additional support for the country rock surrounding the stope but also to provide base for the worker to execute the upper level as can be seen in the Figure 1.3. Thus, strength of filling material is not the main consideration in filling type selection. Fill type ranging from waste rock, pneumatic fill or hydraulic fill can be selected depend on the several factors such as availability, cost of transportation, curing time, etc. (Crandall 1992). As a result, overhand variant has cost advantage compare to the underhand ones. Two underground gold mines in Indonesia apply overhand variant in their operation. The name of the company is PT Aneka Tambang UBPE Pongkor and PT Cibaliung Sumberdaya. The hydraulic backfill is applied in their operation with the average cost of 1.5-1.6 $/ton. The average gold grade of PT Aneka Tambang UBPE Pongkor is 13 gr/ton while PT Cibaliung Sumberdaya is 8 gr/ton which lowers than the average grade of gold mined by PT Nusa Halmahera.

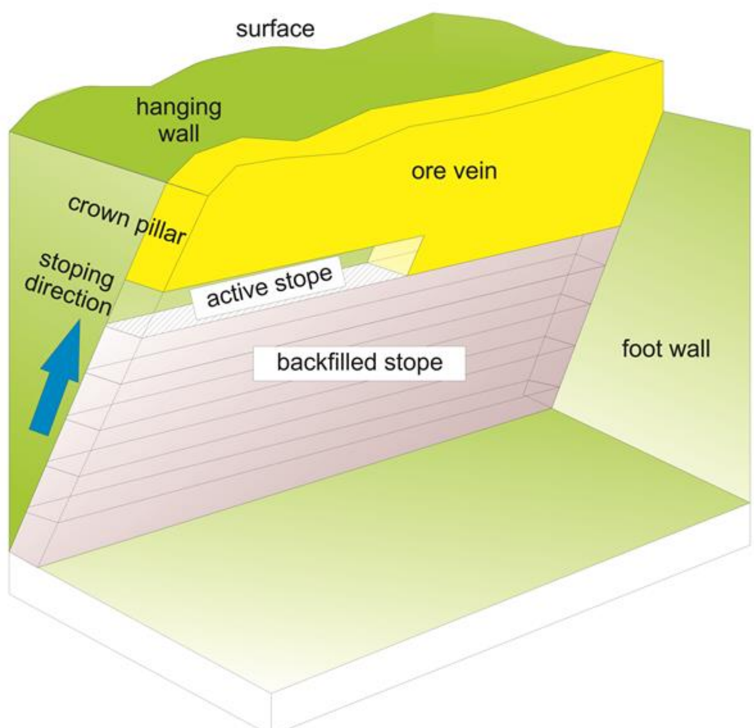

Figure 1.3. Schematic of overhand cut and fill underground mining method.

1.2. Subsidence Related to the Cut and Fill Underground Mine Operation

As explained earlier, subsidence in protected forest due to underground mining is strictly prohibited. Having backfilling in the operation has given cut and fill a preference than the other method to withstand this issue. However, there are records of several surface subsidence cases due to application of this method in the past. It is important to understand the cause of this subsidence to make sure that it is not occurred when implemented in protected forest.

Bell et al. (2000) reported both continuous and discontinuous subsidence have taken place above shallow gold mine in the Johannesburg area. One of the causes is collapse of timber supported stope due to deteriorated timber props causing subsidence at surface area. Since mining is taken above the district area, government limits the permissible heights of proposed buildings in relation to the depth of mining below a site to prevent the damage.

In Indonesia, there are not so many recorded data regarding subsidence cases due to cut and fill mining method. Subsidence occurred in the PT Cibaliung Sumberdaya Contract of Works (CoW) area but not related to their cut and fill operation as can be seen in Figure 1.4(a). A collapse of gophering stope in the vein made by illegal miners is the cause of this subsidence. The subsidence affects the mining operation of PT Cibaliung Sumberdaya by causing a wet muck to one of its opening. Remedial action is then taken by sealing the subsidence area with concrete along with the grouting from surface as can be seen in Figure 1.4(b) even though the company does not have obligation to conduct remedial.

(a) (b)

Figure 1.4. (a) Surface subsidence due to gophering stope collapse. (b) Remedial action taken by concreting and grouting the subsidence.

From the two cases, subsidence is potentially to occur in the cut and fill operation. The cause is stope collapse. Actually, it is not only in the cut and fill but also in any other methods that situation of the underground opening collapse may result in the occurrence of subsidence. Subsidence more likely to occur when an opening is collapsed at shallow depth as happen in the shallow gold mine in Johannesburg area and shallow gophering stope made by illegal miners as reported above. Singh and Dhar (1997) have reported that subsidence in form of sinkholes occurs in different coalfield with the maximum depth between 24.4 m and 101.5 m, which strengthen this statement. When a stope fails in the cut and fill, there is a possibility that failure will continue until the rock mass separates uppermost stope with the surface, which named crown pillar. This will lead to surface subsidence especially when stope is located near surface area or crown pillar thickness is slender.

In common practice, increasing crown pillar thickness could be a way to prevent subsidence. However, part of crown pillar in cut and fill mining method which is directly located above the stope formed by valuable ore body. Increasing its thickness will increase the stability, yet reduce mining recovery since higher volumes of ore body are left behind as a pillar. Therefore, maintaining stope stability during extraction is the key to prevent subsidence in cut and fill application. Further detail studies need to be carried out on stope and crown pillar stability in the cut and fill area that aim to prevent stope failure during extraction as well as maximize recovery of the crown pillar.

1.3. Dissertation Objectives

Following perspective given in the previous section, the objectives of the dissertation are listed below:

1. Understanding stress condition around stope and crown pillar area of cut and fill mine at shallow depth for different condition such as stoping direction, geological condition, vein geometry and stress ratio.
2. Investigating effectiveness of rock support as common countermeasure method for stope instability in different mine condition.

3. Introducing alternatives countermeasure method for stope instability that suitable to be applied at the protected forest condition.

1.4. Outline of the Dissertation

To achieve objectives of dissertation, six chapters are presented in this study. Following the first chapter, the rest of the chapters will be described as follow:

- Chapter 2 describes the stress condition around stope and crown pillar area in cut and fill. The focus will be given on the stress condition for different stoping direction, geological condition, vein geometry and stress ratio. The result will be fundamental for discussing the effectiveness of countermeasure method in the next chapters.
- Chapter 3 reveals the effectiveness of rock support as common countermeasure method for stope instability in different mine condition. Two types of rock support which are active and passive type was simulated to stabilize stope and crown pillar. The advantages and disadvantages of rock support along with its effectiveness for different mine condition will be discussed in this chapter.
- Chapter 4 introduces the application of sill pillar as countermeasure method for stope instability as well as maximizing crown pillar recovery. The application will be simulated at several conditions where it is found that the crown pillar supported by rock support in previous chapter is not optimum. The reason behind improvement of stope and crown pillar stability will be explained in this chapter.
- Chapter 5 introduces alternative countermeasure for stope at shallow depth which is column grout. Determination of material properties after grouted by column grout which used for numerical analysis is given in this chapter. Effectiveness of column grout application is discussed and the possibility to minimize its effect to the surface of protected forest is presented.

Finally, Chapter 6 summarized the conclusion from each chapter as general conclusion of the dissertation.

1.5. Conclusion

With the growing number of mineralization finding in the protected and conservation forest, mining sector faces challenge to maximize the benefit from natural resources development while at the same time minimize the negative impacts to the environment. Cut and fill mining method can be a solution to this challenge as it offers protection from subsidence through the application of fill material. Among two widely practiced variations, overhand is more preferable than underhand one due to its lower cost. However, when the rock is categorized as weak rock, the application of underhand is become unavoidable.

Having backfilling in its application, subsidence still potentially to occur in cut and fill due to collapse stope, especially when the stope is in shallow depth. Failure of shallow depth stope may continue until the rock mass separates uppermost stope with the surface, which named crown pillar. Increasing crown pillar thickness could be a way to prevent surface subsidence. However, part of crown pillar in cut and fill mining method which directly located above the stope is formed by ore body. Increasing its thickness will increase the stability, yet reduce mining recovery since higher volumes of ore body are left behind as a pillar. Therefore, maintaining stope stability during extraction is the key to prevent subsidence in cut and fill application.

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Chapter 2

Effect of Stoping in Cut and Fill Mining Method under Different Mine Condition

The first chapter reveals the key to prevent subsidence that may occur at cut and fill method is by maintaining stope stability, especially in shallow area. Stoping in overhand and underhand variant and/or in different mine conditions (e.g. geological, vein geometry and stress ratio) may experience different stress condition around stope and crown pillar. This stress condition will influence the stope and crown pillar stability. It is important to understand stress condition at different stoping direction and condition around mine area to help in designing an appropriate countermeasure method for stope instability. Prior to this goal, fundamental study was carried out by using numerical simulation.

A case study of cut and fill mining for gold vein type deposit is used for numerical simulation. The simulation is carried out by using Finite Element Method. Program named $PHASE^2$ is utilized to simulate two dimensional models. A 200 m square numerical model with 5 m width vein dipping in 75^o as shown in Figure 2.1 is constructed for simulating both underhand and overhand cut and fill mining method at shallow depth. The vein geometry in the model is based on typical vein geometry in Indonesian cut and fill mine such as Pongkor (Basuki et al. 1994) and Cibaliung. Five meter height stope is then constructed from the bottom into the upper part of the vein. This stope will be excavated later in a sequence to simulate underhand or overhand variants. The mined out stope will be backfilled. The crown pillar area cannot be exactly distinguished along the model as it depends on the location of the uppermost stope from the stability analysis. Therefore, the boundary is indicated by using the dash line in the schematic.

All material is set to comply with the Mohr-Coulomb failure criterion. The displacement in the lateral limit of the model is only permitted in the y-directions while at the lowest part of the model is only permitted in the x-direction. The surface is set free to move in all directions. Rock mass properties for the basic model can be seen in Table 2.1. The rock mass properties were obtained from laboratory testing of rock samples taken from Cibaliung Gold Mine. To obtain basic behavior of stope and crown pillar under different mine condition, stress ratio within the basic model is set to be one and stope is left unsupported.

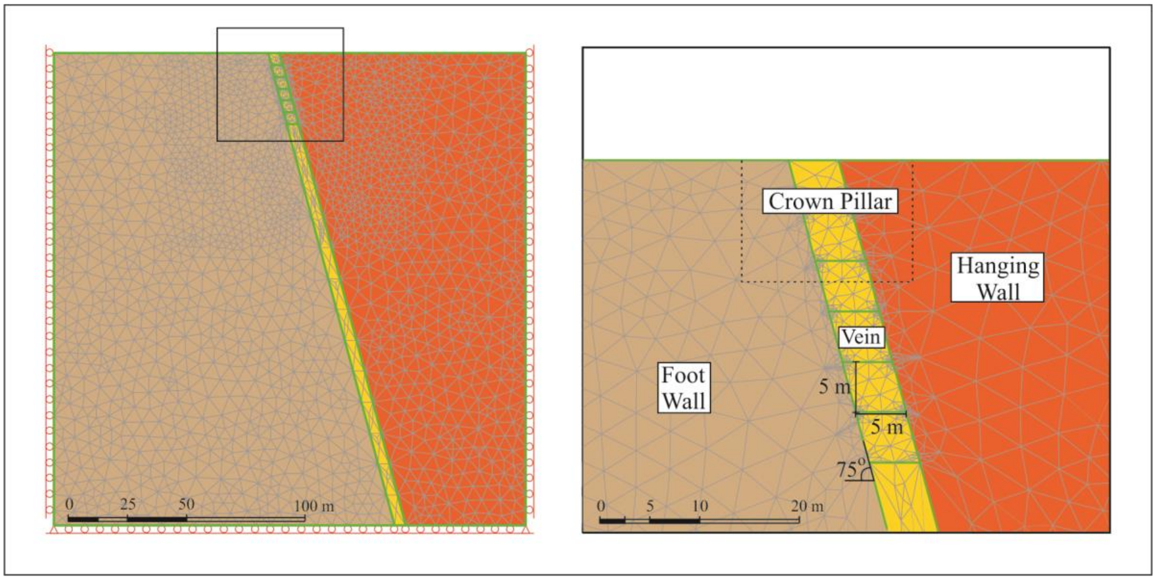


Figure 2.1. Basic model for numerical simulation.

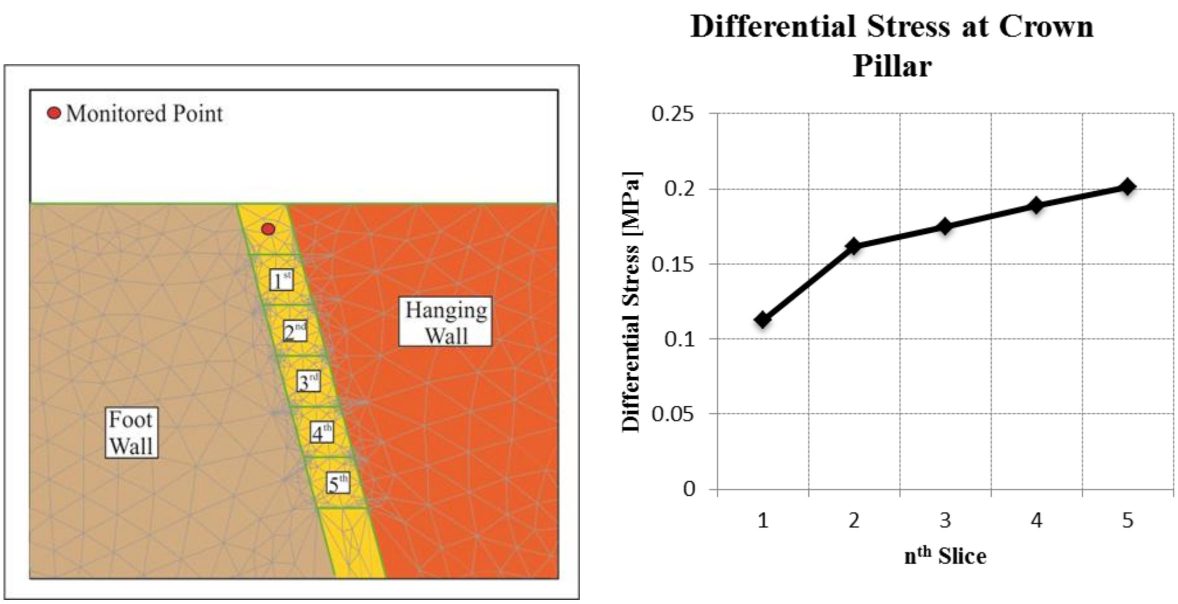
Table 2.1 Rock mass properties for basic model.

Zone	Mohr-Coulomb Parameter				
	C (MPa)	ϕ	σ_t (MPa)	E_{rm} (MPa)	v
Hanging wall	0.145	37.2	-0.002	245	0.3
Foot wall	0.20	44.4	-0.0046	614	0.3
Quartz Vein	0.39	57	-0.026	3563	0.2
Hydraulic Fill*	0.07	6.9	0	181	0.2
Cemented Hydraulic Fill*	3.72	8.8	-1.5	4382	0.3

Notes: C = rock mass cohesive strength; ϕ = rock mass friction angle; σ_t = uniaxial tensile strength of rock mass; E_{rm} = Young's modulus of rock mass; v = Poisson's Ratio; * = intact properties.

2.1. Stress Condition and Ground Behavior around Stope and Crown Pillar in Underhand Variant

To simulate underhand variant, stope at numerical model is excavated from the upper slice with the sequence shown in Figure 2.2(a), leaving 5 m vein as crown pillar. The mined out stope is backfilled by using cemented hydraulic fill. Differential stress (difference between major and minor in plane principal stresses, $\sigma_1 - \sigma_3$) at the center of the crown pillar, as shown by red dot in Figure 2.2(a), is then recorded as stope progressing downward. Figure 2.2(b) presents the change of differential stress at the monitored point during stoping progression.



(a) (b)

Figure 2.2. (a) Sequence of stopping and location of monitored point (b) Differential stress at monitored point as the stope progressing downward.

Based on the simulation result, the differential stress at the center of crown pillar is increasing steadily as the stope progressing away from the crown pillar. This trend indicates that the induced stress from stope opening is accumulated in the crown pillar area even though stope moving away from the crown pillar. The gradient of curve shows that the amount of induced stress accumulates in the crown pillar is getting smaller as the stope progressing downward. Its effect to crown pillar and stope stability is given in Figure 2.3.

The color in the simulation result shown in Figure 2.3 indicates yielded element contour. The zones in which the stress satisfies the yield criterion are considered as yielded element. By looking at the whole pattern of this yielded element, stope or the crown pillar failure can be determined. A crown pillar is assumed to be fail when yielded elements propagate from the stope until the surface area. If the yielded elements only occur around the stope without propagate to the surface, it means that failure only occurs at stope.

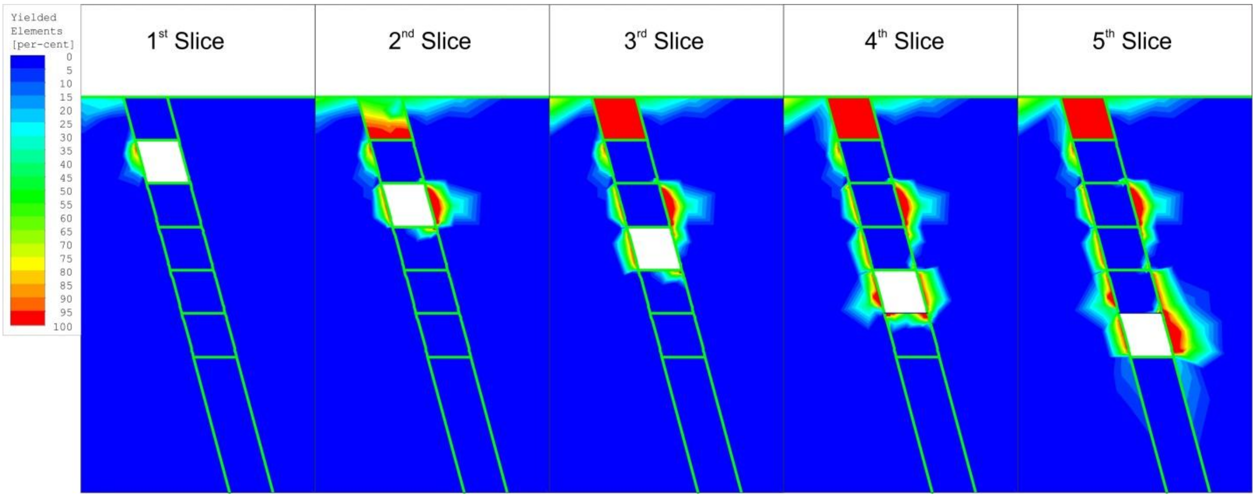


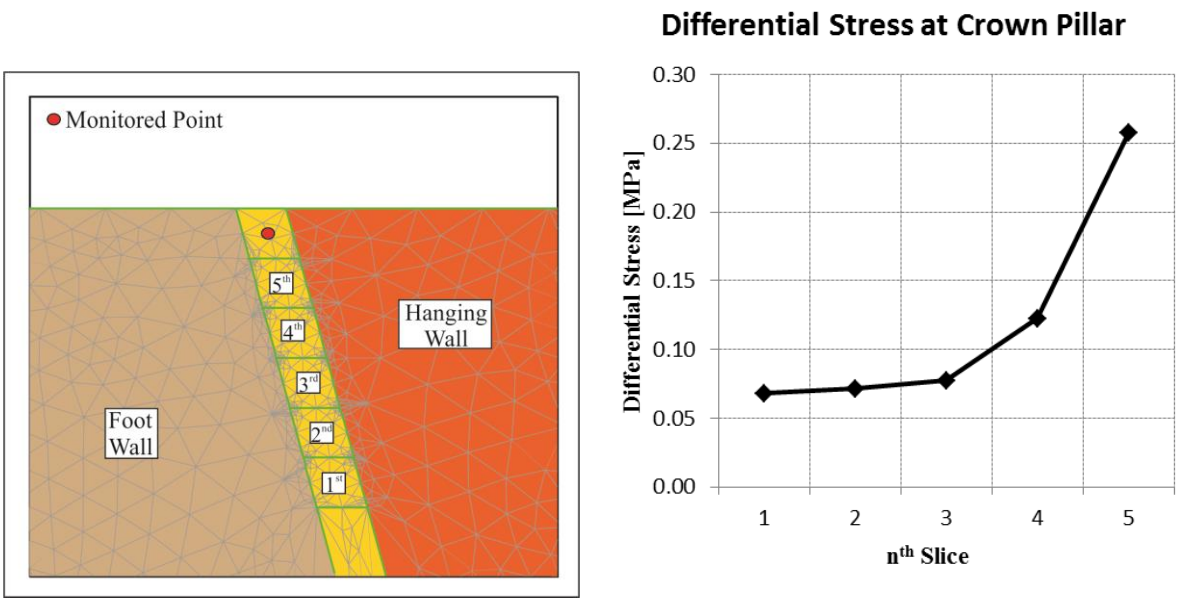
Figure 2.3. Crown pillar and stope stability in underhand variant.

Result in Figure 2.3 shows the crown pillar is in stable condition after the first slice is executed. As mining continued into the second slice, differential stress at crown pillar is increasing as shown in previous Figure 2.2(b) causing the yield zone occurrence. Crown pillar is completely yielded as the third slice is executed. Having completely yielded, the crown pillar cannot be considered as failure since the fill below the crown pillar rock mass is supporting it. If the yielded zone continues until the stope opening then it can be considered that the crown pillar rock mass together with the fill collapse into the stope opening causing subsidence.

Stope in simulation of underhand cut and fill is relatively in good condition. The roof is completely stable from the first until the last slice. Only small yielded areas occur in the hanging wall side of several slices. In general, application of cemented hydraulic fill gives a stable condition at roof of the stope during stopping at underhand cut and fill. When the vein rock mass condition is very weak, application of underhand tend to be safer than the overhand one since the roof is strong cemented hydraulic fill. Application of overhand will be risky, especially when support capacity from installed support and reinforcement is not enough to stabilize the weak vein rock mass.

2.2. Stress Condition and Ground Behavior around Stope and Crown Pillar in Overhand Variant

As the stoping direction of overhand is different with the underhand ones, the stress condition around stope and crown pillar will be different. Overhand cut and fill simulation is carried out with the stopping sequence shown in Figure 2.4(a). Hydraulic fill is used to fill the mined out stope in this simulation. The differential stress as the stope progressing upward is recorded at the same place with the previous simulation. The result is shown in Figure 2.4(b).



(a) (b)

Figure 2.4. (a) Sequence of stopping and location of monitored point (b) Differential stress at monitored point as the stope progressing upward.

Figure 2.4(b) indicates differential stress at the crown pillar in overhand variant increases as the stope progressing upward. Induced stress from first stope opening already affects differential stress at crown pillar. The influence of induced stress becomes higher as the stope moves closer into the monitored point. As the consequence, the crown pillar is more likely to fail as the stope progressing upward. Crown pillar and stope stability from the result of numerical simulation are given in Figure 2.5.

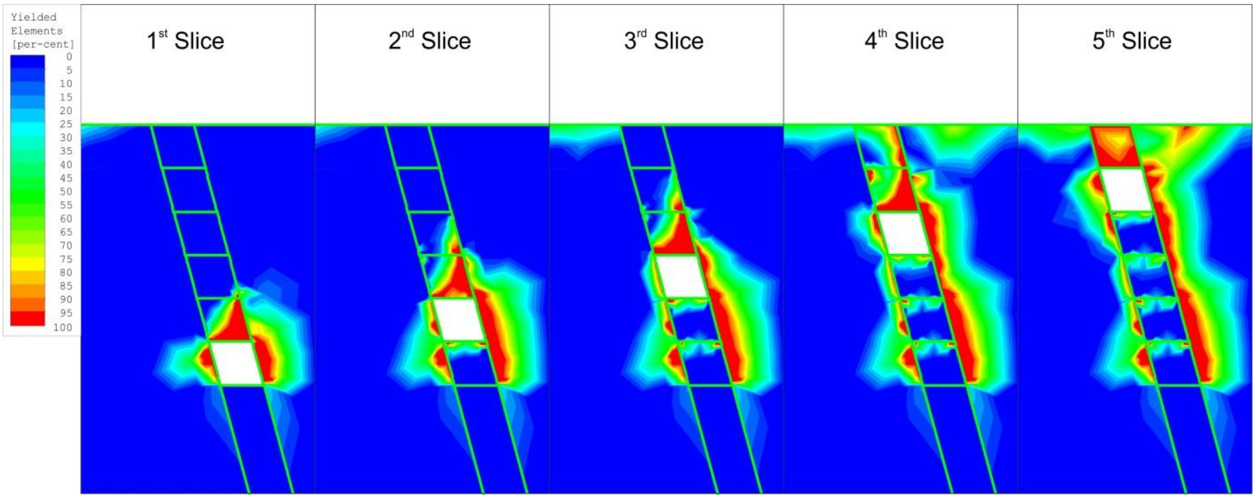


Figure 2.5. Crown pillar and stope stability in overhand variant.

The result of simulation shows instability occurs both at stope and crown pillar area. When the first slice is opened, fully yielded zone, which indicated by red color, occurs at stope roof and wall. However, the failure does not propagate to the surface because the failure rock mass form a stable arch, as can be seen from the yielded zone pattern above the stope. At this level, failure only occurs at stope while crown pillar remains stable. As the stope moves to the upper level and the differential stress becomes higher, crown pillar failure occurs exactly when the 4th slice is executed. The fully yielded zone propagates until the surface. From the pattern, it can be expected that sinkhole subsidence occurs at the surface. The failure pattern in the fifth slice suggests sinkhole subsidence widened into the hanging wall area. It can be expected that subsidence will cover a larger area if the crown pillar failure occurs due to the fifth slice excavation.

Compared with the stope and crown pillar stability in underhand variant, the one in overhand variant is more unstable. Stope roof during stoping at the underhand is completely stable with no yield zone occurrence. On the contrary, stope roof in unsupported overhand cut and fill simulation is unstable. Moreover, the yield zone around the wall is also worse than the one in underhand simulation. This result suggests that underhand cut and fill give a better stability condition to the stope and crown pillar. However, as mentioned in the previous chapter, it should be noted that the application of cemented hydraulic fill in underhand could be very costly, which cause its application is limited to the weak rock condition only. The following simulations of various mine conditions, such as geological, vein geometry and stress ratio, are carried out for overhand cut and fill since more concerns on its stope and crown pillar stability is needed.

2.3. Effect of Stoping in Cut and Fill Mining Method for Various Vein Dips

Numerical simulations of overhand cut and fill in various vein dips are carried out with the aim to understand stope and crown pillar stability in various vein dips to. Models with vein dip of 75°, 62.5°, and 50° are simulated with the same properties and stress ratio as the previous model for cut and fill variation simulation. The simulation result of the stope and crown pillar stability is given in Figure 2.6.

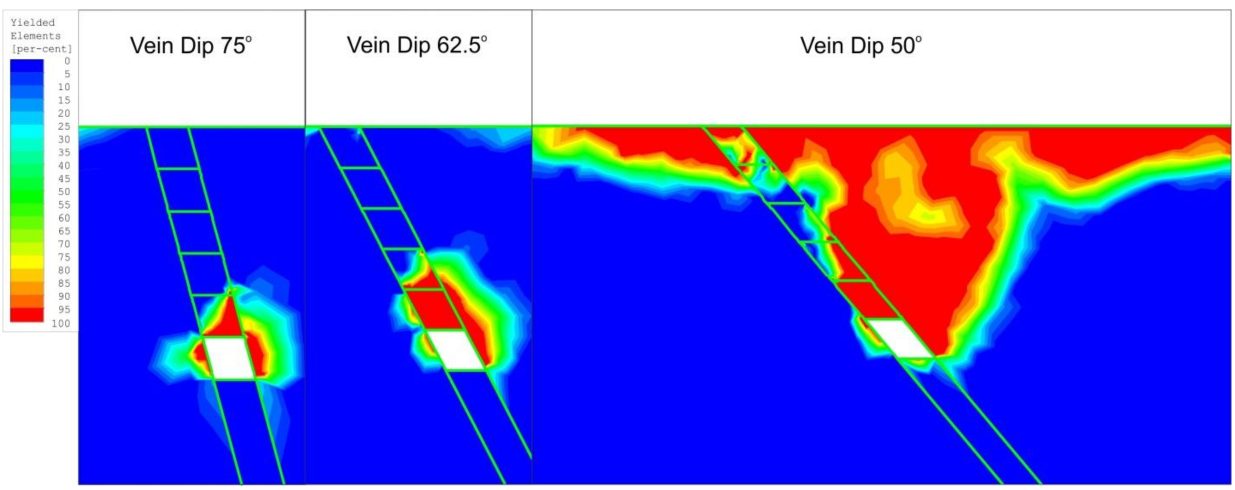


Figure 2.6. Crown pillar and stope stability in various vein dips.

The result suggests that the crown pillar instability is more likely to occur in cut and fill mine with low vein dip. This statement can be drawn from the results that show first slice excavation for a model with vein dip 75° has caused stope failure while for the model with the vein dip 62.5°, the yield element extended further above the stope. In addition, crown pillar failure is identified in the model with vein dip 50°. Large sinkhole subsidence is expected to occur in the hanging wall area as the result of this crown pillar failure. Thus, this result suggests special attention needs to be given on hanging wall when mine at vein with a low dip.

When the stoping is carried out at low vein dip, the hanging wall is more likely to become stope roof along with vein rock mass. Since its properties are the weakest among the other zones, hanging wall can collapse easier than the others. Moreover, stress will be concentrated at hanging wall as shown by stress flow line and trajectories in Figure 2.7. A stress flow line indicates the orientation of major in-plane principal stress along a continuous line. In model with 75^o vein dip, stress concentration is relatively distributed evenly among hanging wall, foot wall and vein. It is shifted more to the hanging wall area as the stoping carried out at lower vein dip, as shown in the stress flow and trajectories for a model with vein dip 50^o.

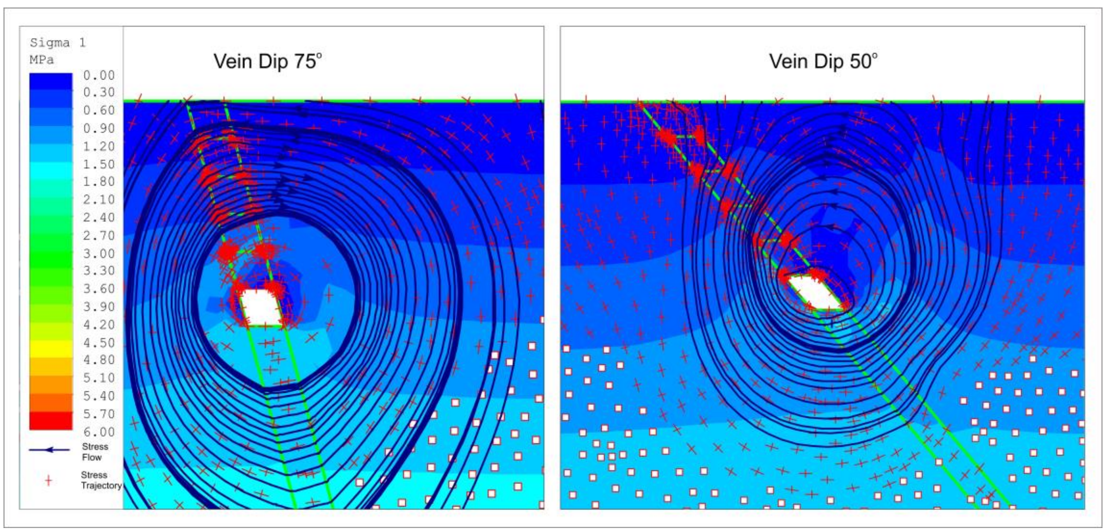
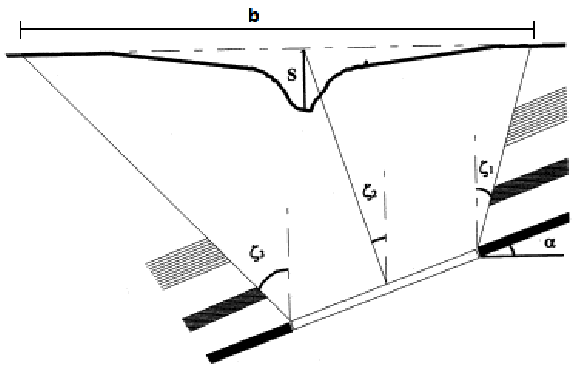


Figure 2.7. Stress flow and trajectories around stope and crown pillar in model with different vein dip.

To characterize subsidence resulted from crown pillar failure in the model with different vein dip, subsidence parameters are measured based on numerical simulation result. Subsidence parameters to characterize subsidence profile are given in the Figure 2.8. The complete subsidence parameters from result of numerical analysis are given in Table 2.2 while the profile is shown in Figure 2.9. The y-axis in Figure 2.9 shows elevation of model surface along x-coordinate (x-axis) after stope excavation. From the subsidence parameter and its profile, it can be expected that subsidence due to crown pillar failure in vein with lower dip covers a wider area. Crown pillar failure in vein with lower dip tends to have higher maximum subsidence value (S_{max}), distance between outer limit of subsidence, and angle of draw. It means the subsidence will cover a larger area than the one in steeper dip. The results also indicate that significant subsidence only occurs when the crown pillar failure occurs as shown in Figure 2.6 for model with vein dip 50°. When it is only stope failure that occurs as result of excavation and stable arch is form as shown by the rest of simulation results, almost no subsidence or only small amount of subsidence occurs at surface of the model.



- S : Subsidence value (m)
- α : *Dip* of deposit (…°)
- b : Distance between outer limit of subsidence (m)
- ς_1 : *Angle of draw* (…°)
- ς_2 : S_{max} *deviation* (…°)

Figure 2.8. Subsidence profile due to inclined layer (after Peng 1978).

Table 2.2 Subsidence parameters from simulation of models with different vein dip.

Vein Dip (…°)	S_{max} (m)	b (m)	S_{max} Deviation (MPa)	Left Angle of Draw (…°)	Right Angle of Draw (…°)
75	0.08	-	-	-	-
62.5	0.2	19.2	11.7	23.3	17.7
50	1.2	25.6	6.5	28.3	21.7

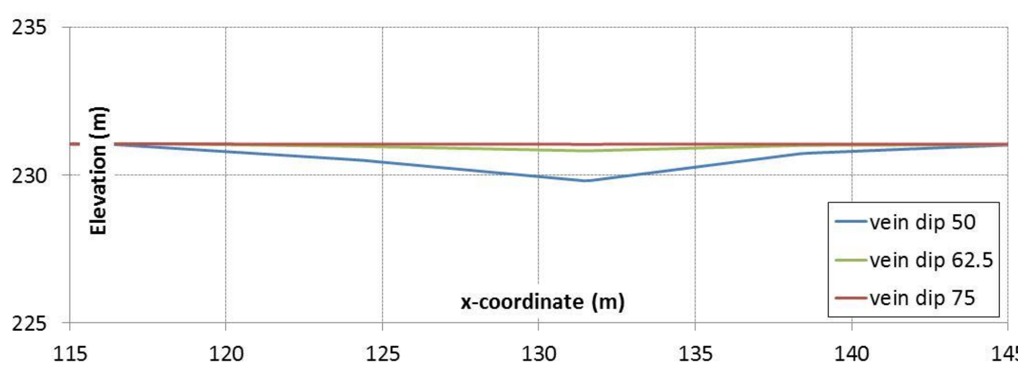
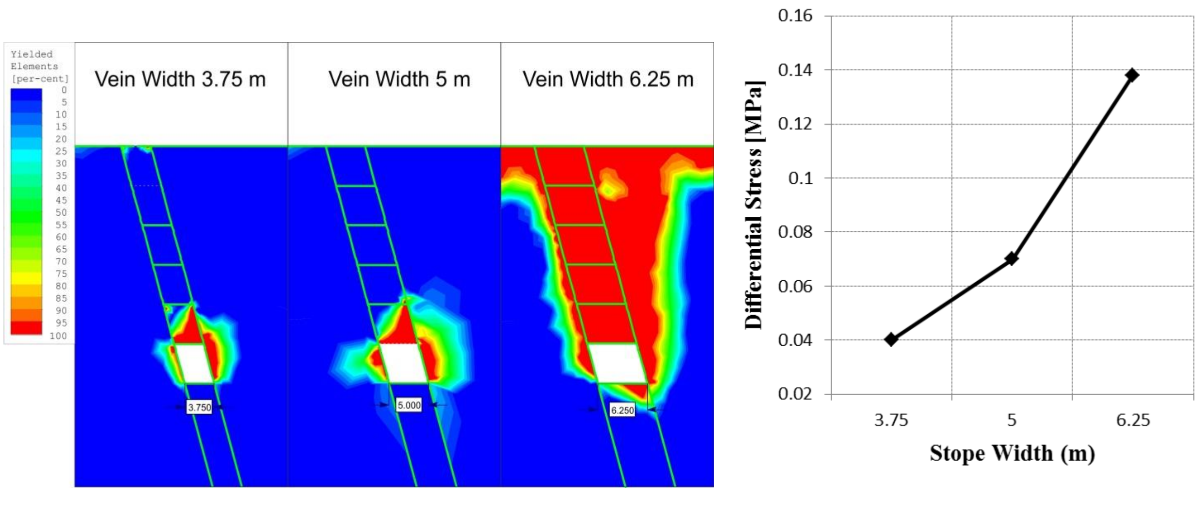


Figure 2.9. Subsidence profile from simulation of models with different vein dip.

2.4. Effect of Stoping in Cut and Fill Mining Method for Various Stope Widths

Another parameter that might influence the crown pillar stability is the stope width. Wider vein results in wider width of stope that leads to higher induced stress. Simulations with various vein widths are carried out and the result is given in Figure 2.10. As the stope opening becomes wider that follows the vein width, the differential stress at the center of crown pillar becomes higher (Figure 2.10(b)). This increasing value of differential stress at the crown pillar is due to higher induced stress resulted from wider stope opening.

The crown pillar failure is more likely to occur when the stope opening wider. From simulation with vein width 6.25 m, crown pillar failure occurs when the first slice is executed. Meanwhile, the rest of the models show only stope failure occurs when the first slice is executed. Moreover, subsidence profile for each simulation, as can be seen in Figure 2.11, show highest subsidence value (around 0.4 m) and largest area identified at model with vein width 6.25 m where crown pillar failure occurs. No significant subsidence can be found at the surface of model with vein width 3.75 and 5 m since stable arch is formed after the stope failure. This result highlights the importance of maintaining stope stability when stoping carried out at wide vein width since it will result in higher environmental impact at the surface.



(a) (b)

Figure 2.10. (a) Crown pillar and stope stability in various stope widths (b) Differential stress measured at the center of the crown pillar for various stope widths.

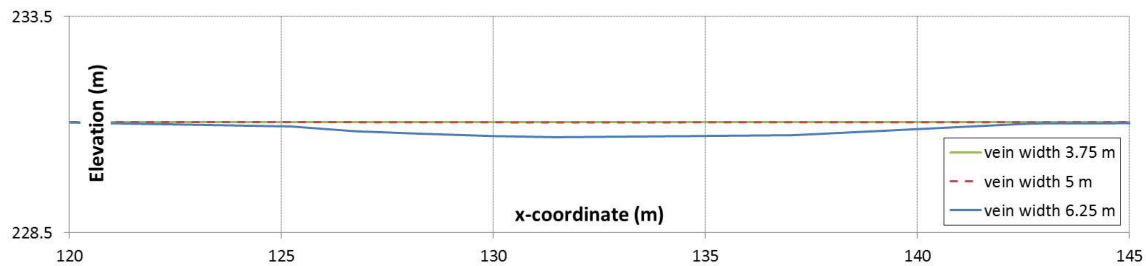


Figure 2.11. Subsidence profile from simulation of models with different vein width.

2.5. Effect of Stoping in Cut and Fill Mining Method for Various Geological Conditions

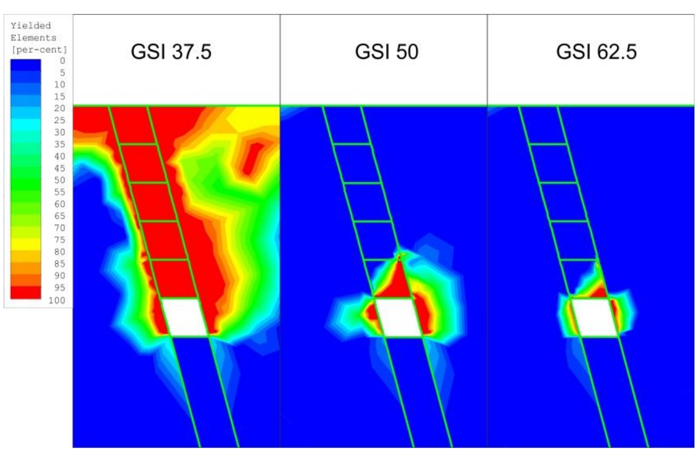
Different geological condition could result in different stress condition around the stope and crown pillar area. Simulations with various geological conditions are carried out to understand stress condition in different geological condition. Geological condition is represented by Geological Strength Index (GSI) parameter (Marinos and Hoek 2000; Hoek et al. 2013). Different GSI values are simulated ranging from 37.5, representing blocky rock mass with fair joint surface quality, to 62.5, representing very blocky rock mass with good joint surface quality. The other rock mass properties are then determined for each GSI by using Hoek and Brown Failure Criterion (Hoek and Wood 1987; Hoek and Brown 1988; Hoek 1990; Hoek et al. 2000; Hoek and Diederichs 2006). The summary of rock mass properties, which are used in this simulation, is provided in Table 2.3.

The result of the simulations is summarized in Figure 2.12. The result suggests that as the geological condition become more severe, the potential of crown pillar failure will be higher. Mining the first slice has caused crown pillar failure in the model with GSI 37.5 while only stope failure occurs in the model with GSI 50 and 62.5. In addition, from the comparison between the model of GSI 50 and 62.5, the stope in model with GSI 62.5 is in better condition having a smaller yield area. The reason behind this result is better stress condition as shown in Figure 2.12(b). Model with higher GSI, represents better geological condition, has a lower differential stress at center of crown pillar. Therefore, it can be expected that stress around the whole model is also lower than the stress around model with lower GSI. Moreover, displacement at center of stope roof perimeter for model with GSI 62.5 is the lowest among all of the models. 3.8 mm displacement at center of stope roof was recorded at the model with GSI 62.5 while 1.8 cm and 3.3 m displacement was recorded for model with GSI 50 and 37.5 respectively. At the surface, subsidence is not expected to occur for models with GSI 62.5 and 50 as can be seen from surface subsidence profile of each model given in Figure 2.13. Their subsidence profile along with other models where stable arch was formed indicates that if stable arch was formed, it is almost certain that subsidence will not occur at surface. The certainty will be higher if the stope is in stable condition. Therefore, stope stability is the key to prevent subsidence.

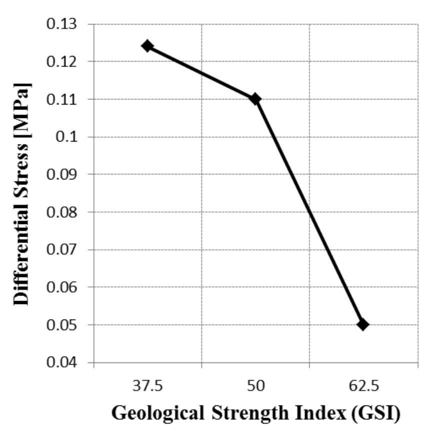
Table 2.3 Rock mass properties for simulation of model with various geological conditions.

Geological Strength Index (GSI)	Zone	Hoek Brown Parameter				Mohr-Coulomb Parameter				
		σ_{ci} (MPa)	m_b	s	a	C (MPa)	ϕ	σ_t (MPa)	E_{rm} (MPa)	v
37.5	Hanging wall	2	2.68	0.00096	0.51	0.12	33.55	-0.00072	107.6	0.3
	Foot wall	5	2.68	0.00096	0.51	0.16	40.73	-0.0018	269	0.3
	Quartz Vein	29	2.68	0.00096	0.51	0.30	53.76	-0.01	1560.3	0.2
50	Hanging wall	2	4.19	0.0038	0.50	0.145	37.19	-0.0018	245.7	0.3
	Foot wall	5	4.19	0.0038	0.50	0.20	44.43	-0.0046	614.4	0.3
	Quartz Vein	29	4.19	0.0038	0.50	0.39	57.01	-0.026	3563.4	0.2
62.5	Hanging wall	2	6.55	0.015	0.50	0.17	40.81	-0.0047	461.3	0.3
	Foot wall	5	6.55	0.015	0.50	0.24	47.92	-0.011	1153.1	0.3
	Quartz Vein	29	6.55	0.015	0.50	0.54	59.68	-0.068	6688.3	0.2

Notes: σ_{ci} = uniaxial compressive strength of intact rock material; m_b, s, a = material constant for Hoek-Brown Failure Criterion; C = rock mass cohesive strength; ϕ = rock mass friction angle; σ_t = uniaxial tensile strength of rock mass; E_{rm} = Young's modulus of rock mass; v = Poisson's Ratio.



(a)



(b)

Figure 2.12. (a) Crown pillar and stope stability in various geological conditions (b) Differential stress measured at the center of the crown pillar for various geological conditions.

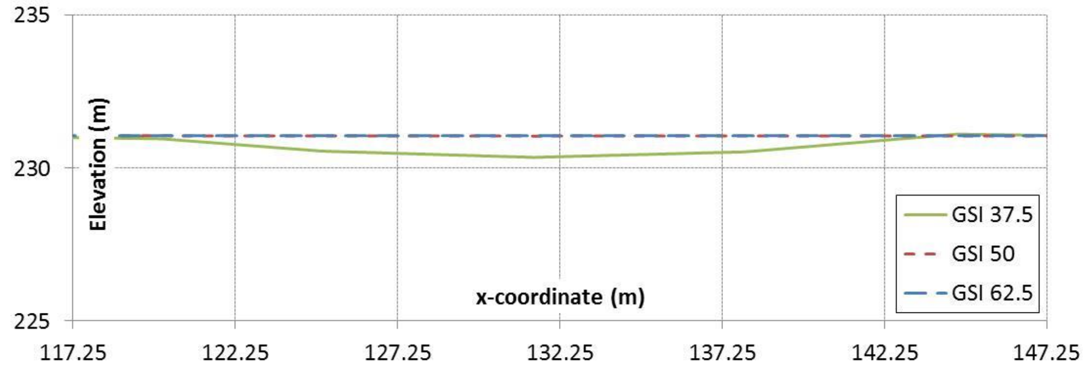
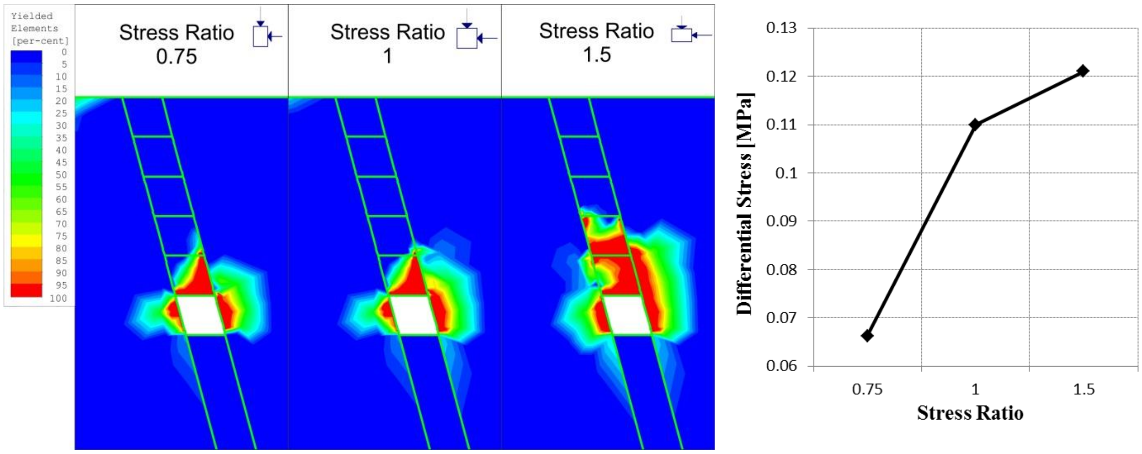


Figure 2.13. Subsidence profile from simulation of models with different geological condition.

2.6. Effect of Stoping in Cut and Fill Mining Method for Various Stress Ratios

Stress ratio (k) determines the stress concentration around stope and the crown pillar area. Figure 2.14(a) shows the result of simulations for the model with different stress ratio. Stress ratio below one indicates a high vertical stress condition around stope and the crown pillar area. On the contrary, stress ratio above one indicates high horizontal stress condition around stope and the crown pillar area. It is difficult to differentiate the result for model with stress ratio 0.75 and 1. However, it is clear from the comparison of model with stress ratio 1.5 and 0.75 that the stope roof in model with a higher horizontal stress ratio will have more severe condition than the one with higher vertical stress ratio.

Figure 2.14(b) shows the differential stress increase as the stress ratio increases. The reason can be described from the stress flow and trajectories shown in Figure 2.15. The stope opening causes an induced stress in tangential direction to occur around stope and the crown pillar area. Induced stress at the crown pillar and stope roof is relatively in horizontal direction. Therefore, if the stope is opened in higher horizontal stress condition, the differential stress will be higher. On the contrary, if the stope is excavated in the high vertical stress area, then the induced stress at crown pillar and stope roof is in the opposite direction causing a lower differential stress. This result suggests more supporting capacity will be needed to stabilize stope and crown pillar in higher stress ratio condition.



(a) (b)

Figure 2.14. (a) Crown pillar and stope stability in various stress ratios (b) Differential stress measured at the center of the crown pillar for various stress ratios.

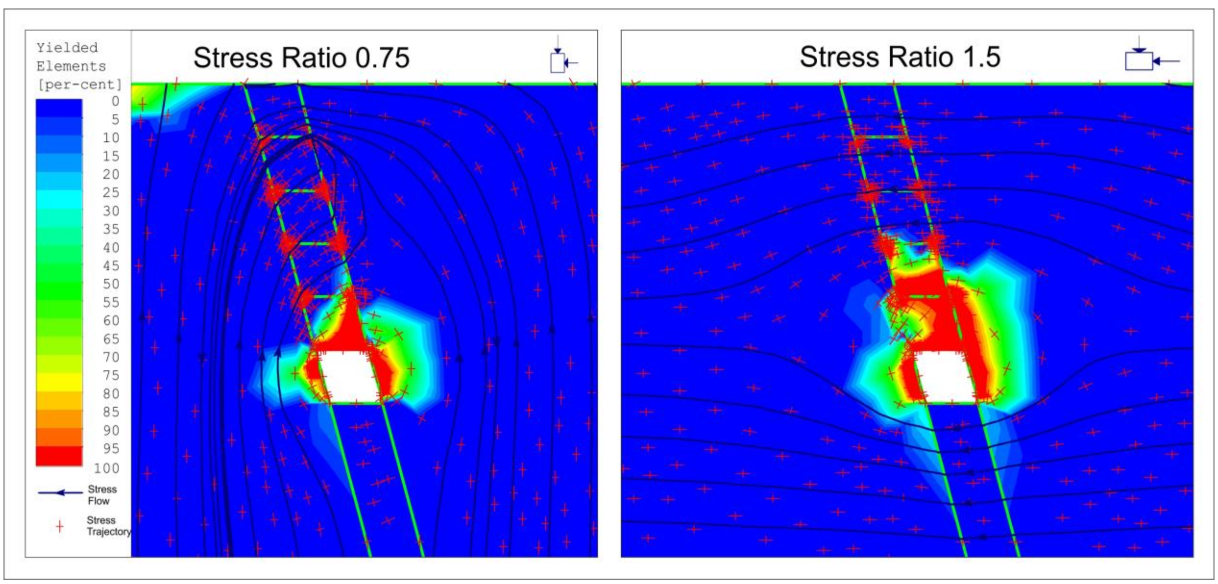


Figure 2.15. Stress flow and trajectories around stope and crown pillar in model with different stress ratio.

Subsidence cannot be identified at the surface of all models since no crown pillar failure occur from the simulations. This result shows that stope failure not always causing subsidence at the surface. Only if the failure continues to the crown pillar area and reach surface then it will result in subsidence. For the stope area, model with stress ratio 1.5 gives the highest displacement at the center of stope roof with 4.6 cm followed by model with stress ratio 1 with 1.8 cm and model with stress ratio 0.75 with 1.6 cm, respectively.

2.7. Effect of Various Fill Types to Stope and Crown Pillar Stability

Previous chapter reveals that various filling materials can be used for overhand variant. Therefore, it is interesting to study the effect of various filling materials to stope and crown pillar stability. Two different filling materials which are hydraulic fill and cemented hydraulic fill with different properties shown in Table 2.1 were simulated as the filling material in the overhand simulation. In Indonesian gold mining companies, hydraulic fill is produced by mixing tailing from the processing plant with water to form slurry. The slurry is transported into the stope which is ready to be backfilled by using pipeline. The mixture consists of 60-80% solid while the rest are water. Meanwhile, addition of cement and additive is added for the cemented hydraulic fill with ratio around 3-18% cement and 7-9% additive. Having an addition of cement and additive, cemented hydraulic fill is stronger and cured faster than hydraulic fill.

The simulation is carried out with the same model used in Section 2.2. To see whether there is an improvement to stope and crown pillar stability, the backfilling material properties after the stope progressing upward is changed into cemented hydraulic fill. Two slices which are second and fourth slice are evaluated to see the effect of cemented hydraulic fill to stope and crown pillar stability, respectively. The result is given in Figure 2.16.

From the comparison of second and fourth slice mining with different filling material, it can be seen that the effect of having stronger filling material to the stope stability is not clear. There is only a small improvement on the stope floor when cemented hydraulic fill, which has stronger properties than hydraulic fill, is used as filling material. No improvement can be identified on the wall and roof side of the excavated stope. Moreover, the crown pillar failure still occurs after the fourth slice is executed even when the stronger filling material is used. Therefore, it can be concluded that properties of filling material have no effect to the stope and crown pillar stability in overhand variant. The selection of filling material in overhand variant should be based on economical and practical reason only without considering stability reason.

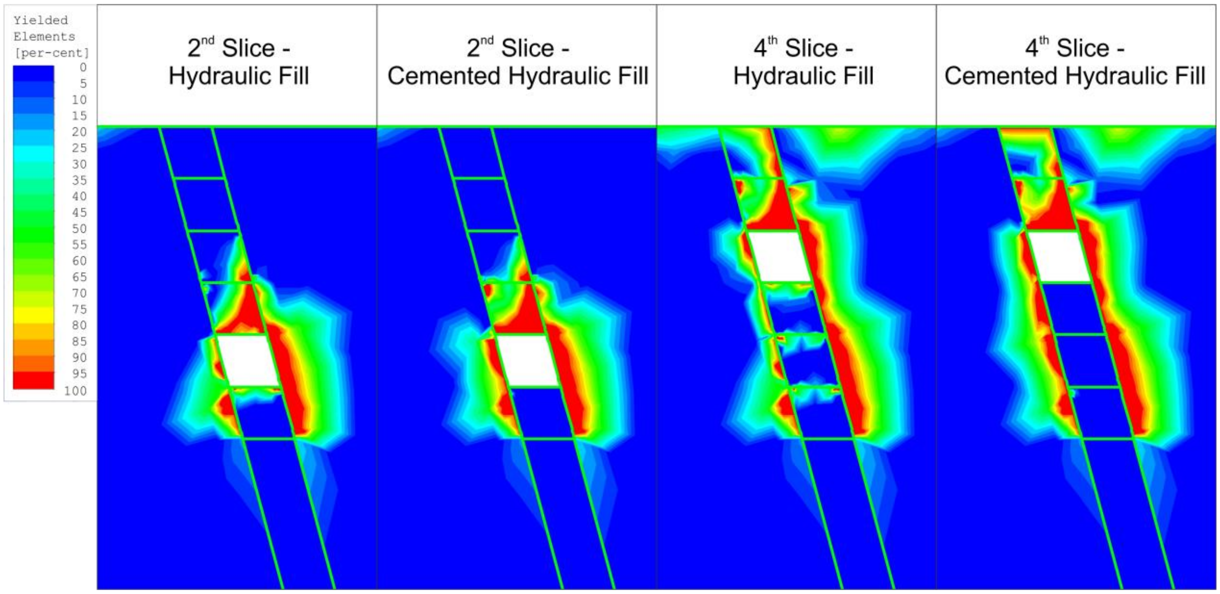


Figure 2.16. Comparison of stope and crown pillar stability with different filling material.

2.8. Conclusion

Differential stress at crown pillar increases as the stope progressing downward in underhand cut and fill or upward in overhand cut and fill. The accumulations of induced stress from the stope opening are the cause of this specific crown pillar characteristic in cut and fill mine. Underhand variant gives a better stability condition during stoping progress due to the application of strong filling material. However, as mentioned in the previous chapter, it should be noted that the application of strong filling material in underhand could be very costly causing its application limited to the weak rock condition.

Simulation of overhand cut and fill with various mine condition such as geological, vein geometry, stress ratio and filling material has been carried out. The results suggest crown pillar failure is more likely to occur at cut and fill mine in the lower vein dip, wider vein width, more severe geological condition, and higher stress ratio. Moreover, the simulation of overhand with different filling material has concluded that properties of filling material have no effect to the stope and crown pillar stability. Subsidence were found at the surface of several models where the failure reaches crown pillar area. If stable arch is formed after the stope is failed, it is almost certain that subsidence will not occur at surface based on simulation results. The certainty will be higher if the stope is in stable condition. Therefore, stope stability is the key to prevent subsidence. This result highlights the importance of rock support and other countermeasure methods to stabilize stope and crown pillar in various mine conditions which will be discussed in the next chapters.

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Chapter 3

Active and Passive Type Rock Support as Countermeasure for Stope Instability in Crown Pillar Area

Simulation results in the second chapter provide fundamental characteristics of stope and crown pillar ground behavior in overhand and underhand cut and fill and in different mine condition. Both crown pillar and stope failure were found from several simulations of overhand cut and fill and some of them causing subsidence at the surface. Appropriate countermeasure method needs to be studied to prevent crown pillar and stope instability in the various condition that may occur at cut and fill mine.

The most common countermeasure method to stabilize stope or other underground opening is rock support. This chapter will investigate the effectiveness of rock support as countermeasure method for stope instability in crown pillar area. Rock support is mainly categorized into active and passive type (Hoek, 1987). Both types of rock support will be simulated to support stope that previously simulated in the second chapter. Its effectiveness will be evaluated not only from its capability to stabilize stope and crown pillar but also to maximize the crown pillar recovery in overhand variant.

3.1. Active Type Rock Support

Active type rock support is type of rock support where the supporting elements are integral part of the reinforced rock mass (Hoek, 1987). This type of rock support will be yielded as the rock deforms. Its installation in the rock will conserve as well as improve the overall rock mass properties from within the rock mass. Mechanically anchored rock bolts, grouted or friction anchored dowels, grouted cables are among rock support which are categorized as active type rock support. Each type of active type rock support offers different practical advantages and disadvantages along with suitability for a different rock mass and stress condition.

From economical point of view, active type rock support is preferred to the passive type support system due to its lower cost. In Indonesian cut and fill gold mine where split set and cable bolt is widely used as an active type rock support, split set costs around 15.8 US$/unit while cable bolt costs around 10 US$/unit. At the other hand, passive type rock support such as H-beam costs 1,000 US$/unit and shotcrete costs 1,578.95 US$/$m^3$. As a roughly comparison, installation of each rock support in 1 m length stope with the similar geometry in previous chapter will cost 853.2 US$ for split set (0.5 m x 0.5 m spacing), 540 US$ for cable bolt (0.5 m x 0.5 m spacing), 2,000 US$ for H-beam (1 m spacing), and 2,368.4 US$ for shotcrete (10 cm thickness). Moreover, active type rock support is also very practical to be installed at the boundary of opening. Installation of passive type rock support can be time consuming. As for the utilization of cable bolt in stoping, installation did not need to be carried out at every level. For example, 10 m length cable bolt can be installed at roof of 5 m height stope. The bolt can be cut as the stope progressing upwards so that the next slice does not need to install cable bolt anymore. Due to its economical and practical advantages over passive type rock support, the use of active type rock support will potentially become more popular in Indonesian cut and fill mines.

To understand the effectiveness of active type rock support as countermeasure for stope instability in crown pillar area, two different active type rock supports which are split set and cable bolt are simulated in the numerical model. Their properties are given in Table 3.1. The properties were obtained from the split set and cable bolt that are generally used in Indonesian cut and fill gold mine.

Table 3.1. Split set and cable bolt properties for numerical model.

Split Set Properties		Cable Bolt Properties	
Length (m)	2.4	Type	Fully Bonded
Diameter (mm)	46	Length (m)	5-10
Typical Tensile Capacity (kN)	178	Diameter (mm)	19
Minimum Tensile Capacity (kN)	120	Bolt Modulus (MPa)	200,000
Bolt Modulus (MPa)	200,000	Tensile Capacity (MN)	0.1
Bond Shear Stiffness (MN/m/m)	12,000	Residual Tensile Capacity (MN)	0.01
Yield Strength (MPa)	588		
Recommended Initial Anchorage (kN)	53–89		

3.2. Passive Type Rock Support

Passive type rock support has a different working principal with the active one. Its system is external to the rock and responds to inward movement of the rock surrounding the excavation (Hoek, 1987). It will give a reactive force to the excavation boundary due to the inward movement (Windsor and Thompson, 1993). This type of rock support stabilizes the stope by limiting the displacement that may further deteriorate the rock mass properties. Range of supporting capacity is heavily dependent on the material used for the support system.

Being more expensive than the active ones, passive type rock support has very limited application such as in very loose ground. In such condition, the installation of active type support system might not effective since it will not anchor properly. Another reason to apply passive type rock support is high stress condition occurred around the opening. In high stress condition, large displacement may occurs at boundary of opening and the rock will continue to move even after supported by active type rock support. Application of passive type rock support will limit the rock movement in such condition thus improving the opening stability.

Two variants of passive type rock supports which are H-beam and shotcrete are simulated in the numerical simulation. Those two variants are the most widely used in Indonesian cut and fill gold mine and their properties are given in Table 3.2.

Table 3.2. H-beam and shotcrete properties for numerical model.

Shotcrete Properties		H-beam Properties	
Young's Modulus (GPa)	21	Young's Modulus (GPa)	200
Poisson's Ratio	0.15	Poisson's Ratio	0.3
Compressive Strength (MPa)	35		
Tensile Yield (kN)	20		
Residual Yield (kN)	10		

3.3. Parametric Study

To obtain objectives defined earlier in this chapter, parametric study is carried out for a model with different geological condition, stress ratio, vein dip and width. Both active and passive type support system will be installed to find optimum rock support design in stabilizing stope and crown pillar as well as maximizing crown pillar recovery. Installation of active type will be the first priority since it has economical and practical advantages over the passive one. If it is found that stope supported by active type is in unstable condition, rock support will be modified by providing more active or passive type rock support. To maximize the crown pillar recovery, upper slice of stable stope supported by rock support will be excavated with the same rock support design. Additional active and passive type rock support will be given if it is found the currently analyzed stope is unstable. This iterative process will be carried out until it is found that stope or crown pillar failure still occur with the strongest variant of passive type rock support. The optimum crown pillar is the rock mass height above the last stable stope from the iteration process.

The determination of stable or unstable stope and crown pillar in the following simulations will be based on yield zone resulted from numerical simulation. Thus it will be somewhat qualitative. The stope will be considered as failure when the yield zone pattern forms an arch shape at roof or wall side as can be seen in Figure 3.1. This shape indicates the rock above or on the side of the stope potentially fail then stop up until certain level due tendency to make stable arch. For the crown pillar, failure is confirmed when the yield zone pattern continues from the surface until the stope opening. The shape can be sinkhole, caving or other shape of failure. Displacement of rock around stope perimeter and subsidence value at the surface will be used as supporting data when the yield zone pattern did not give a clear indication on stope and crown pillar stability.

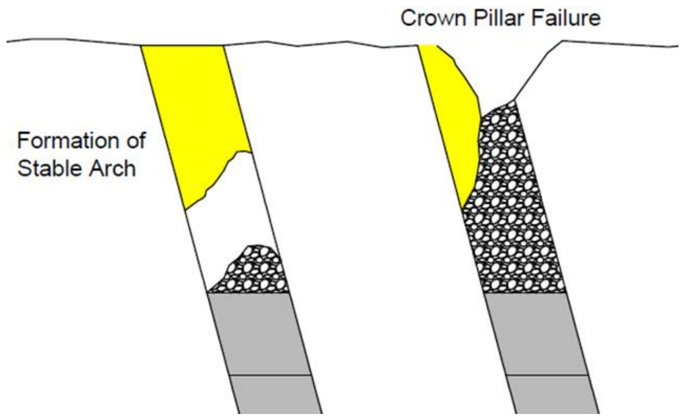

Figure 3.1. Typical yield zone patterns that considered as failure if occur at stope or crown pillar model.

3.3.1. Parametric Study of Numerical Model with Different Geological Condition

Parametric study in this section is carried out to understand the effectiveness of rock support as countermeasure method for stope failure in different geological condition. The basic numerical model used in the second chapter will be simulated with 5 different rock mass properties. The results are compared with each other to obtain a general conclusion of rock support effectiveness in different geological condition. As in the second chapter, rock mass properties were changed with geological condition as the basis. The rock mass properties used in this simulation are summarized in the Table 3.3. Stress ratio during a parametric study of numerical model with different geological conditions is set to be one.

Table 3.3. Rock mass properties for parametric study of numerical model with different geological condition.

Geological Strength Index (GSI)	Zone	Hoek Brown Parameter				Mohr-Coulomb Parameter				
		σ_{ci} (MPa)	m_b	s	a	C (MPa)	ϕ	σ_t (MPa)	E_{rm} (MPa)	v
25	Hanging wall	2	1.71	0.00024	0.53	0.095	29.90	-0.0003	47.9	0.3
	Footwall	5	1.71	0.00024	0.53	0.13	36.73	-0.0007	119.7	0.3
	Quartz Vein	29	1.71	0.00024	0.53	0.23	49.74	-0.004	694.3	0.2
37.5	Hanging wall	2	2.68	0.00096	0.51	0.12	33.55	-0.0007	107.6	0.3
	Footwall	5	2.68	0.00096	0.51	0.16	40.73	-0.002	269	0.3
	Quartz Vein	29	2.68	0.00096	0.51	0.30	53.76	-0.01	1560.3	0.2
50	Hanging wall	2	4.19	0.0038	0.50	0.145	37.19	-0.002	245.7	0.3
	Footwall	5	4.19	0.0038	0.50	0.20	44.43	-0.004	614.4	0.3
	Quartz Vein	29	4.19	0.0038	0.50	0.39	57.01	-0.026	3563.4	0.2
62.5	Hanging wall	2	6.55	0.015	0.50	0.17	40.81	-0.004	461.3	0.3
	Footwall	5	6.55	0.015	0.50	0.24	47.92	-0.01	1153.2	0.3
	Quartz Vein	29	6.55	0.015	0.50	0.54	59.68	-0.07	6688.3	0.2
75	Hanging wall	2	10.23	0.06	0.50	0.21	44.33	-0.01	653.1	0.3
	Footwall	5	10.23	0.06	0.50	0.31	51.14	-0.03	1632.7	0.3
	Quartz Vein	29	10.23	0.06	0.50	0.86	61.67	-0.2	9469.7	0.2

Notes: σ_{ci} = uniaxial compressive strength of intact rock material; m_b, s, a = material constant for Hoek-Brown Failure Criterion; C = rock mass cohesive strength; ϕ = rock mass friction angle; σ_t = uniaxial tensile strength of rock mass; E_{rm} = Young's modulus of rock mass; v = Poisson's Ratio.

3.3.1.1. Geological Strength Index (GSI) 25

Rock mass with GSI 25 is a relatively disintegrated rock mass with poor joint surface quality. It can be expected high capacity of passive type rock support is needed to stabilize both stope and crown pillar. Simulation result of stope supported by the active type rock support for a model with GSI 25 is given in the Figure 3.2. Simulation results in Figures 3.2(a) and 3.2(b) shows crown pillar failure occurs when stopes are supported by split set with 1 m x 1 m and 0.5 m x 0.5 m spacing, respectively. When combination between split set and cable bolt is installed (Figures 3.2(c) and 3.2(d)), yielded element is reduced up to certain level due to increasing support capacity given by cable bolt. However, stope failure still occurs. The active type support system cannot stabilize stope in this geological condition. It is also doubtful whether the active type rock support can be anchored effectively in this kind of condition. Hence, passive type support system was installed. The result is summarized in Figure 3.3.

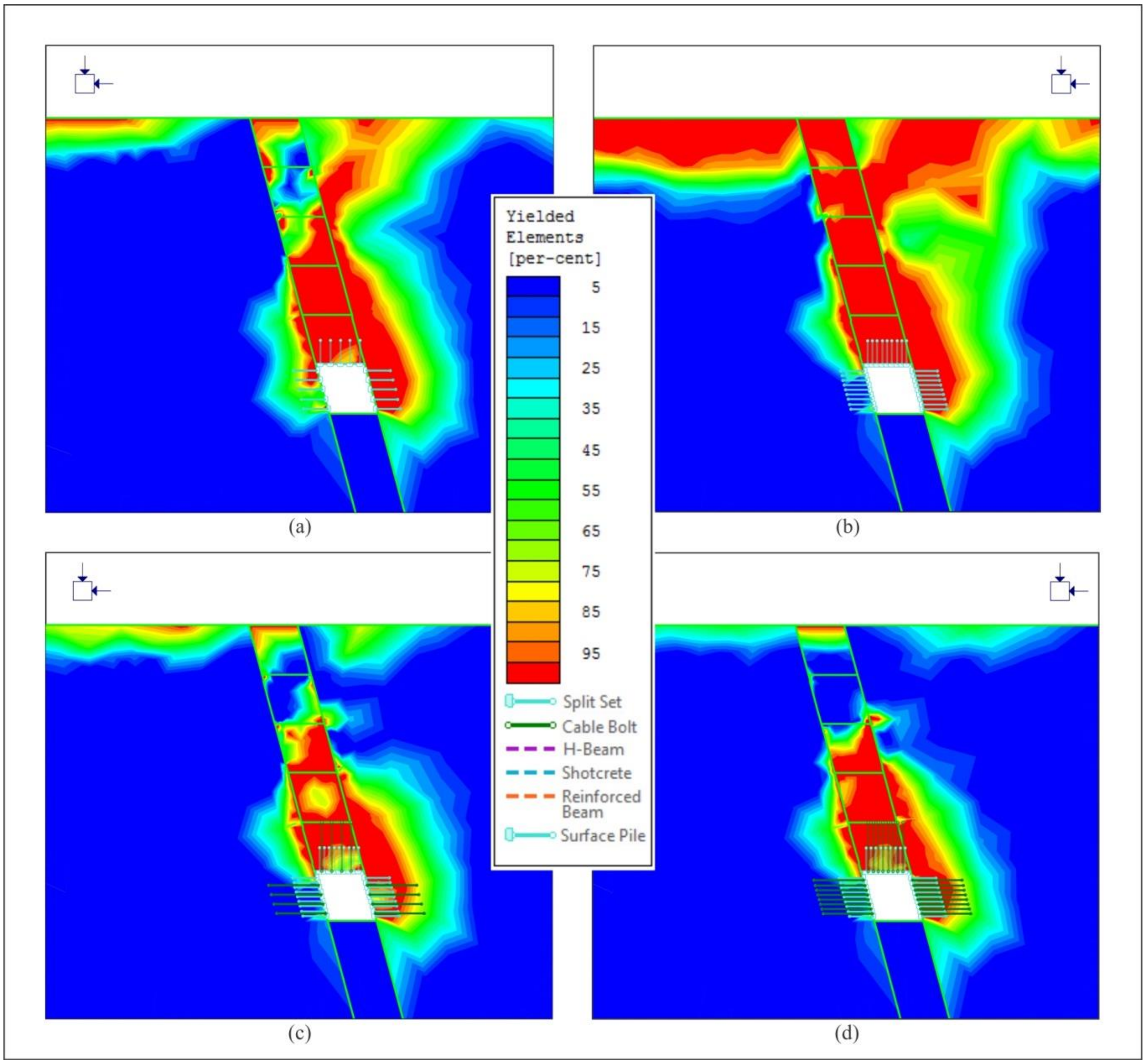

Figure 3.2 Simulation result of stope supported by the active type rock support for a model with GSI 25.

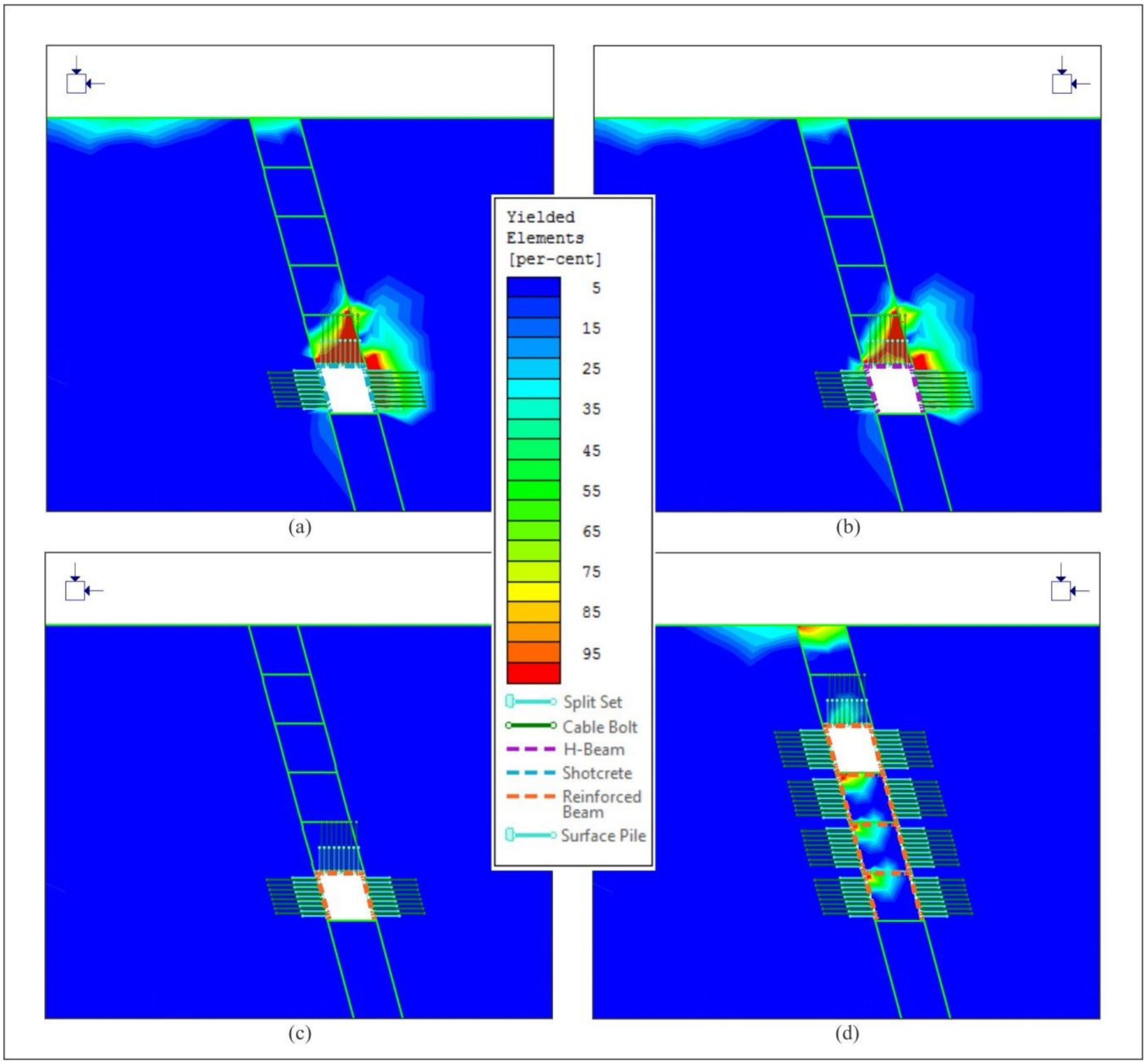

Figure 3.3 Simulation result of stope supported by the passive type rock support for a model with GSI 25.

After supported by the shotcrete or H-beam, large yielded zone at roof still occur as shown in Figure 3.3(a) and 3.3(b). Stope is still in unstable condition. Displacement around 6 cm is recorded at center of roof perimeter at both of models. Several rock support systems are also yielded based on the analysis. Nevertheless, there is a reduction of yielded zone surrounding the stope due to higher support capacity given by those two kinds of passive type rock support. This result suggests passive type rock support with higher supporting capacity is needed. Therefore, reinforced beam is installed as can be seen in Figure 3.3(c). Reinforced beam is constructed from a combination of shotcrete and H-beam which result in higher supporting capacity. From Figure 3.3(c), it can be seen that stope in the first slice is in stable condition. Series of simulation shows that stoping supported by reinforced beam can be carried out until the fourth slice (Figure 3.3(d)). When the fifth slice is executed, the crown pillar shows the occurrence of failure. Therefore, the optimum crown pillar thickness is 10 m with the support system design shown in Figure 3.3(d).

Reinforced beam has the highest supporting capacity among the other previously simulated rock support. However, it is also the most expensive one since it combines both shotcrete and H-beam. As a result, economical aspects must be considered when applying this kind of support system, especially when the ore grade is low. It is also worthwhile to compare its cost with the cost of underhand cut and fill application. If it is found that the cost of underhand is lower than reinforced beam, it is better to apply underhand variant. Safety and practical advantages of underhand variant is the main consideration as already discussed in the first and second chapters. The application of reinforced beam will be omitted in the following simulation due to its high cost.

3.3.1.2. Geological Strength Index (GSI) 37.5

Figure 3.4 shows simulation results of stope supported by the active type rock support for a model with GSI 37.5. Since this model has a better rock mass properties compared with the previous model with GSI 25, supporting capacity needed to support the first slice is not as much as the one in the previous model. The first slice can be supported by split set with 1 m x 1 m spacing as given in Figure 3.4(a). A small portion of yielded element occurs on the roof, but since it did not form an arch shape, it can be considered that the stope is in stable condition.

As the stope progressing upwards in Figure 3.4(b), the induced stress becomes higher because of the accumulation of induced stress from first slice and the second slice. This has caused stope in the second slice failure if the same design with the previous slice is installed. Addition of cable bolt with 0.5 m x 0.5 m spacing along with tighter split set in Figure 3.4(c) can stabilize the second slice. However, failure occurs when the same rock support design is installed to support the third slice as can be seen in Figure 3.4(d). This result clearly shows that as stope progressing upwards more supporting capacity is needed to stabilize the stope.

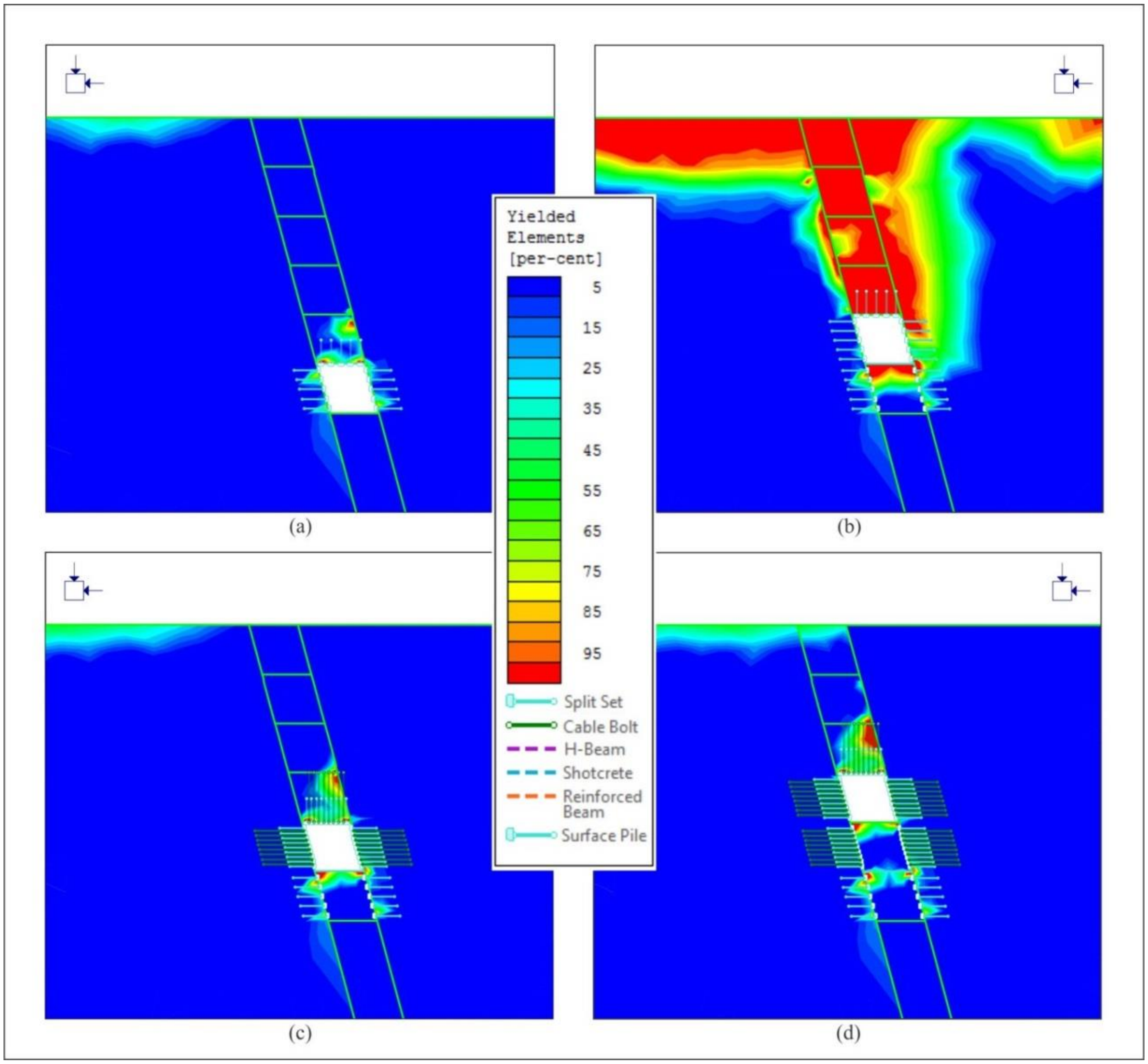

Figure 3.4 Simulation result of stope supported by the active type rock support for a model with GSI 37.5.

The application of the passive type rock support in stabilizing third slice and its upper slice is given in Figure 3.5. Figure 3.5(a) shows addition of shotcrete in third slice can stabilize the stope. However, when the same support system design applied at the fourth slice, both stope and also the crown pillar failures can be identified, as shown in Figure 3.5(b). The installation of H-beam instead of shotcrete in the fourth slice also cannot stabilize the stope and crown pillar as shown in Figure 3.5(c). Based on the simulation result of stope supported by active and passive type rock support, the optimum crown pillar thickness is 15 m with the rock support design shown in Figure 3.5(a).

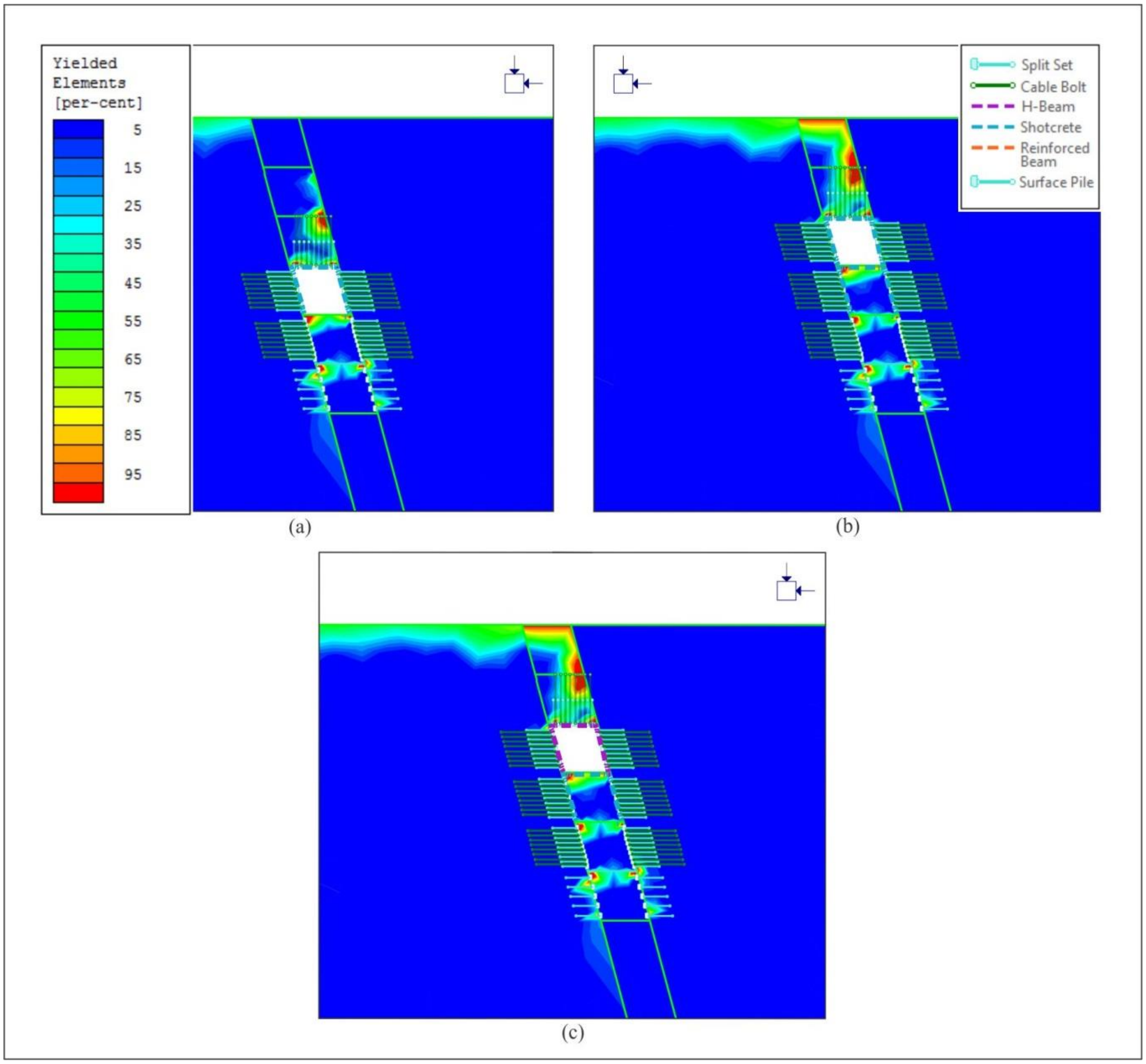

Figure 3.5 Simulation result of stope supported by the passive type rock support for a model with GSI 37.5.

3.3.1.3. Geological Strength Index (GSI) 50

A series of simulation for model with GSI 50 is carried out. Simulation result of stope supported by the active type rock support is given in Figure 3.6. Comparing with the result in

Figure 3.4, it can be seen clearly that active type rock support application is more effective in the model with GSI 50. Figure 3.6(a) show split set with 1 m x 1 m spacing can support stope until the second slice. Roof failure at stope occurs when the same support system design applied at third slice as shown in Figure 3.6(b). Further analysis has shown increasing the split set density into 0.5 m x 0.5 m can stabilize stope at third slice. Both fourth slice and fifth slice can be supported by a combination of split set with 0.5 m x 0.5 m spacing and cable bolt with 1 m x 1 m spacing as shown in Figures 3.6(c) and 3.6(d). Crown pillar is in stable condition even though yielded zone occurs at the surface. Only 3.4 mm displacement recorded at the center of stope roof perimeter at the fifth slice and there are no sign of subsidence occurs at the surface of the model. This result suggests that no passive type rock support is needed to support stope in this model. Optimum crown pillar thickness is 5 m based on this simulation.

Better rock mass condition is the reason why no passive type support system is required to support this model compare with the previous model with GSI 37.5. Thus, supporting capacity needed to stabilize stope is reduced. Moreover, this result also strengthens the previous statement that as stope progresses upward, more support capacity is needed. Stope at lower level needs less active type rock support than the stope at upper level.

3.3.1.4. Geological Strength Index (GSI) 67.5 and 75

Last parametric study of numerical model with different geological condition is carried out for models with GSI 67.5 and 75. These two GSI values represent relatively very blocky to blocky rock mass with fair to good joint surface quality. Nevertheless, the rock mass properties are still better than the previous three models. Figure 3.7 shows simulation results of stope with an active type support system for these two models.

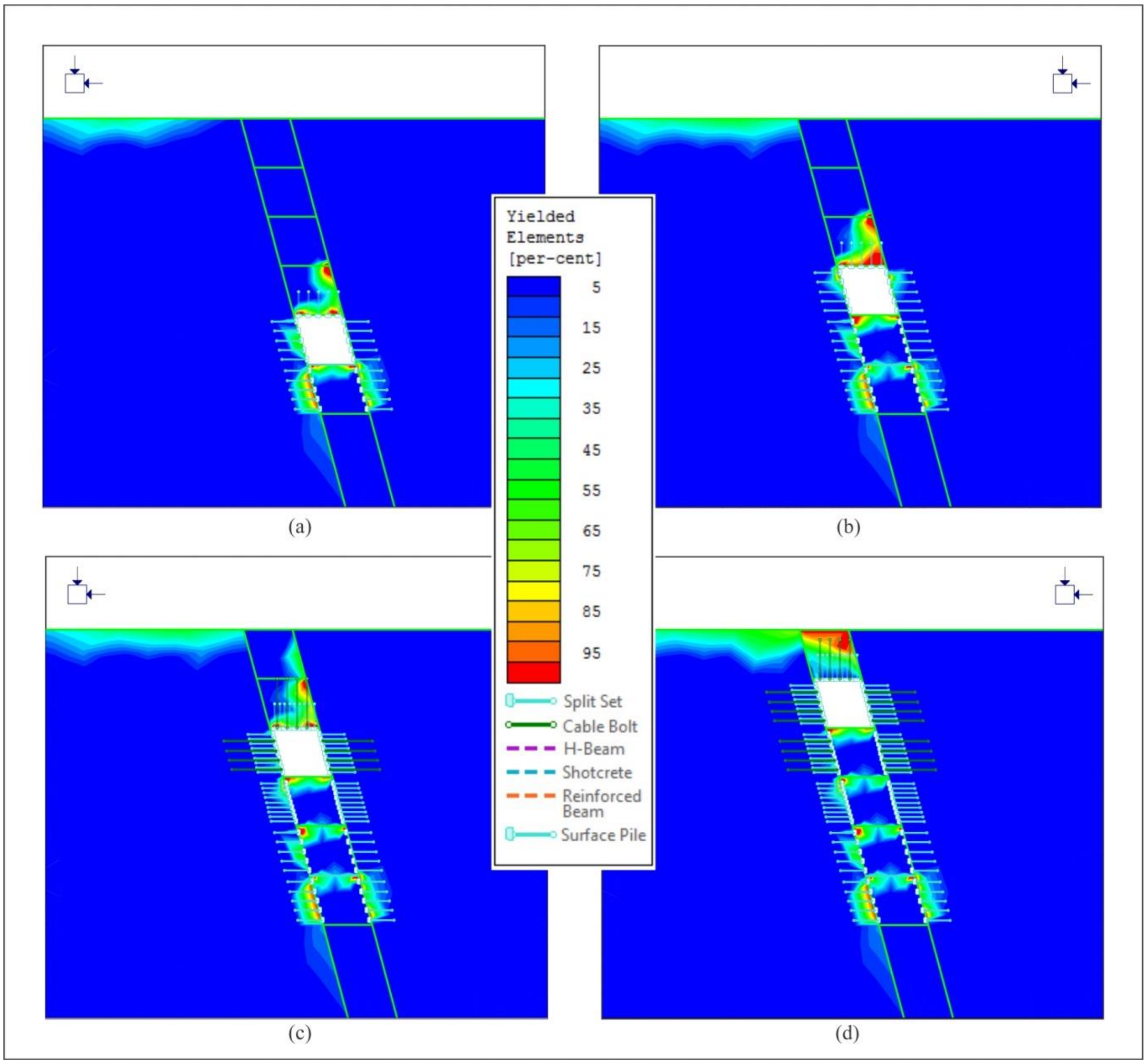

Figure 3.6 Simulation result of stope supported by the active type rock support for a model with GSI 50.

It can be seen clearly that supporting capacity required to stabilize stope is reduced. Split set with 1 m x 1 m spacing in Figure 3.7(a) can support the third slice for a model with GSI 67.5. In Figure 3.6(b), split set with the same spacing cannot be applied to support the third slice for a model with GSI 50. Moreover, 5 m thickness crown pillar is in stable condition with just supported by 1 m x 1 m spacing split set as can be seen in Figure 3.7(b). Similar results are shown for the model with GSI 75 as shown in Figures 3.7(c) and (d). The yield zone contour throughout the model is better than the one in Figures 3.7(a) and (b) since it has better rock mass condition.

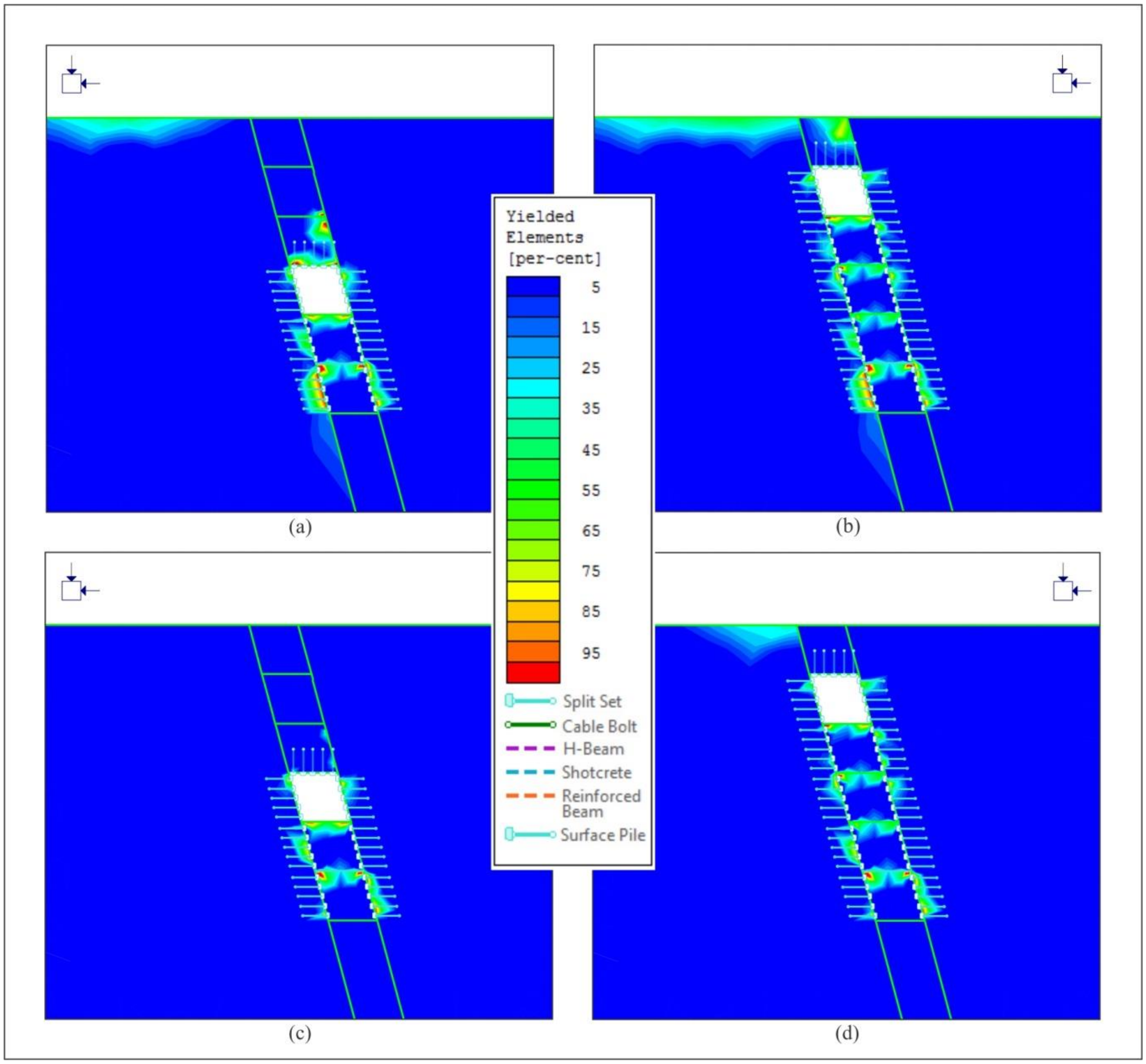

Figure 3.7. Simulation result of stope supported by the active type rock support for models with GSI 67.5 (a and b) and GSI 75 (c and d).

From the simulation results of the model with different geological condition, it can be concluded that in more severe geological condition, more supporting capacity is needed to stabilize stope. Simulation result of model with GSI 25 shows that strongest passive type rock support which is reinforced beam need to be installed to stabilize stope from the first slice. As simulation is carried out for stronger rock mass, i.e. with GSI 37.5 and 50, active type rock support starts to have an effect in stabilizing stope while passive type is only needed to support stope in the crown pillar area for model with GSI 37.5. For a good rock mass condition with GSI above 50, only active type support system is needed to stabilize stope and crown pillar.

When applying rock support as countermeasure for stope instability in crown pillar area, it is important to consider the geological condition of stope and crown pillar rock mass. Active type support needs to be prioritized over the passive one since it has lower cost. As the geological condition become more severe, more supporting capacity is needed by addition of active type rock support or even passive one. A very severe geological condition, for example GSI 25, may lead to excessive need of rock support. In such condition, economical analysis needs to be carried out to compare its cost with the cost of underhand cut and fill application. If it is found that it is more profitable to apply underhand than installing rock support, it is better to apply underhand variant such as reported by Kump and Arnold (2001).

3.3.2. Parametric Study of Numerical Model with Different Stress Ratio (k)

Parametric study in the following sections is carried out in order to understand the effectiveness of rock support as countermeasure method for stope instability under different horizontal to vertical stress ratio. In general, the result will be focused to find appropriate rock support to be installed in the high vertical stress condition and high horizontal stress condition. The k, ratio of horizontal stress to vertical stress, is changed ranging from 0.5 to 2. Stress ratio below one indicates a high vertical stress condition around stope and crown pillar area. On the contrary, stress ratio above one indicates the high horizontal stress condition around stope and the crown pillar area. The rock mass properties used in the parametric study of numerical model with different stress ratio are the ones for GSI 50.

3.3.2.1. Stress Ratio (k) 0.5

Stope and crown pillar in this simulation are surrounded by condition where the value of vertical stress is twice of horizontal stress. Figure 3.8 shows simulation results of stope supported by the active type rock support.

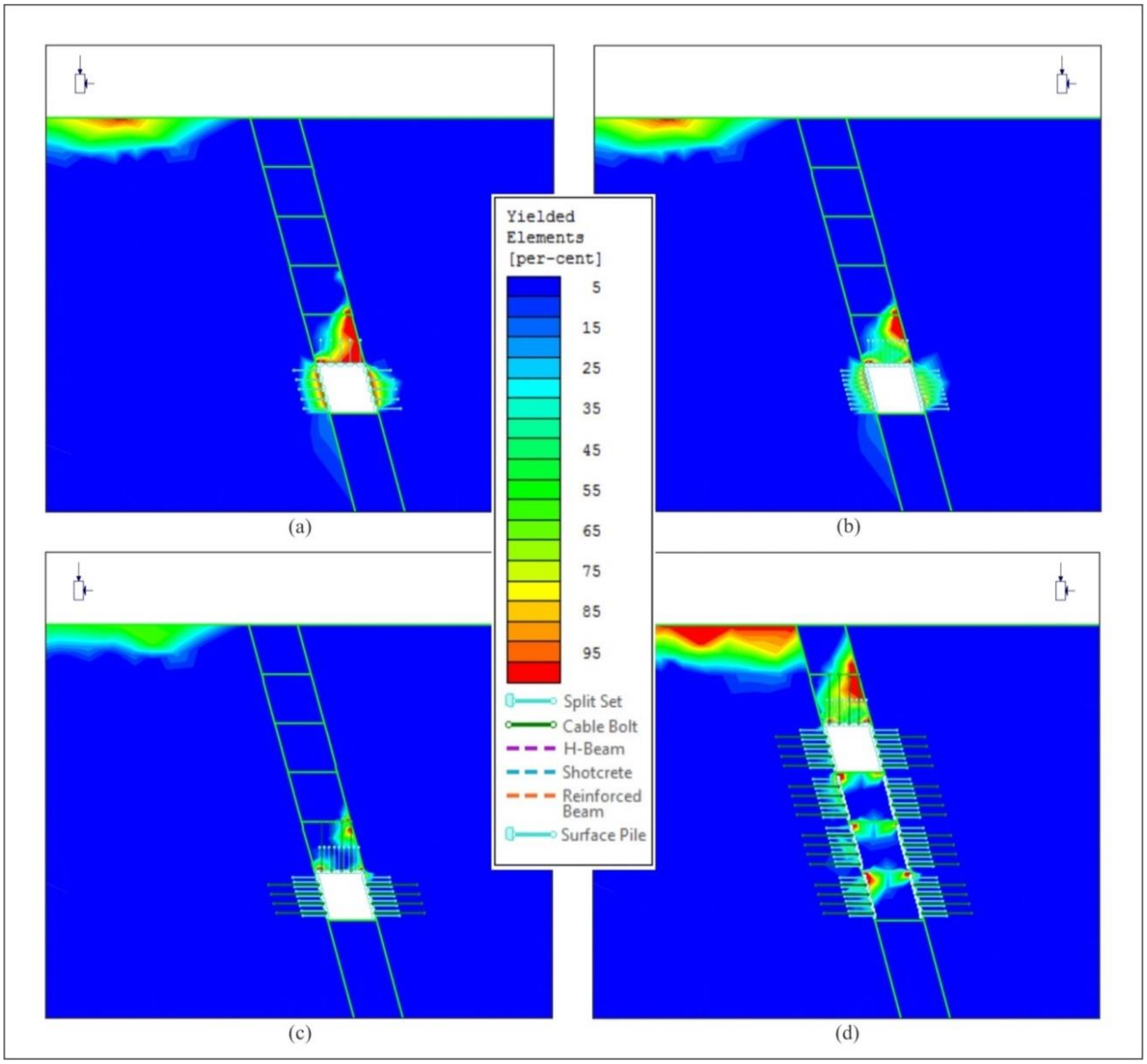

Figure 3.8 Simulation result of stope supported by the active type rock support for a model with stress ratio (k) 0.5.

The split set both with 1 m x 1 m and 0.5 m x 0.5 m spacing cannot be applied to support stope at the first slice as shown in Figures 3.8(a) and 3.8(b), respectively. A combination of 0.5 m x 0.5 m spacing split set and 1 m x 1 m spacing cable bolt need to be applied to support the stope at first slice (Figure 3.8(c)). Based on the analysis, this combination of support system can support the stope until third slice before finally the stope at fourth slice is unstable as can be seen in Figure 3.8(d).

To maximize the crown pillar recovery, passive type support system is installed at stope in fourth slice and the result shown in Figure 3.9. However, it turns out both shotcrete and H-beam cannot give an improvement to stope condition in the crown pillar area. Therefore, 15 m crown pillar thickness needs to be spared to maintain its stability.

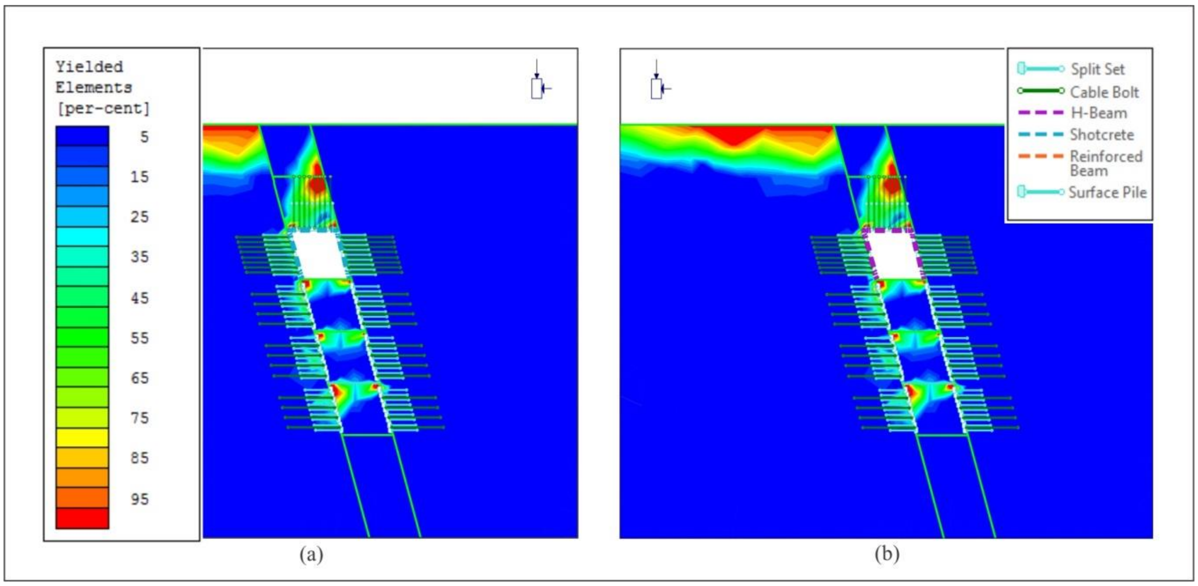

Figure 3.9 Simulation result of stope supported by the passive type rock support for a model with stress ratio (k) 0.5.

3.3.2.2. Stress Ratio (k) 0.75

Another simulation of model with the high vertical stress condition is carried out with stress ratio 0.75. The trend as can be seen in Figure 3.10 is quite similar to the one in Figure 3.8 where active type rock support is capable to support the stope in high vertical stress condition. In Figure 3.10(a), split set with 1 m x 1 m spacing can support stope until the third slice. There is a reduction of required supporting capacity from the one in Figure 3.8 where combination of 0.5 m x 0.5 m spacing split set and 1 m x 1 m spacing cable bolt needs to be applied. This reduction mainly caused by the reduction of vertical stress value surrounding the stope from the twice of horizontal stress value in model with stress ratio 0.5 becomes 1.3 times of horizontal stress value in the current model. From both of the simulations with stress ratio lower than one (k<1), the supporting capacity given by active type is sufficient to support stope in the high vertical stress condition. However, it is insufficient to support stope in the crown pillar area. Increasing density of split set and combine it with cable bolt even with tight spacing cannot improve the stope stability in the crown pillar area as can be seen in Figures 3.10(b)-3.10(d).

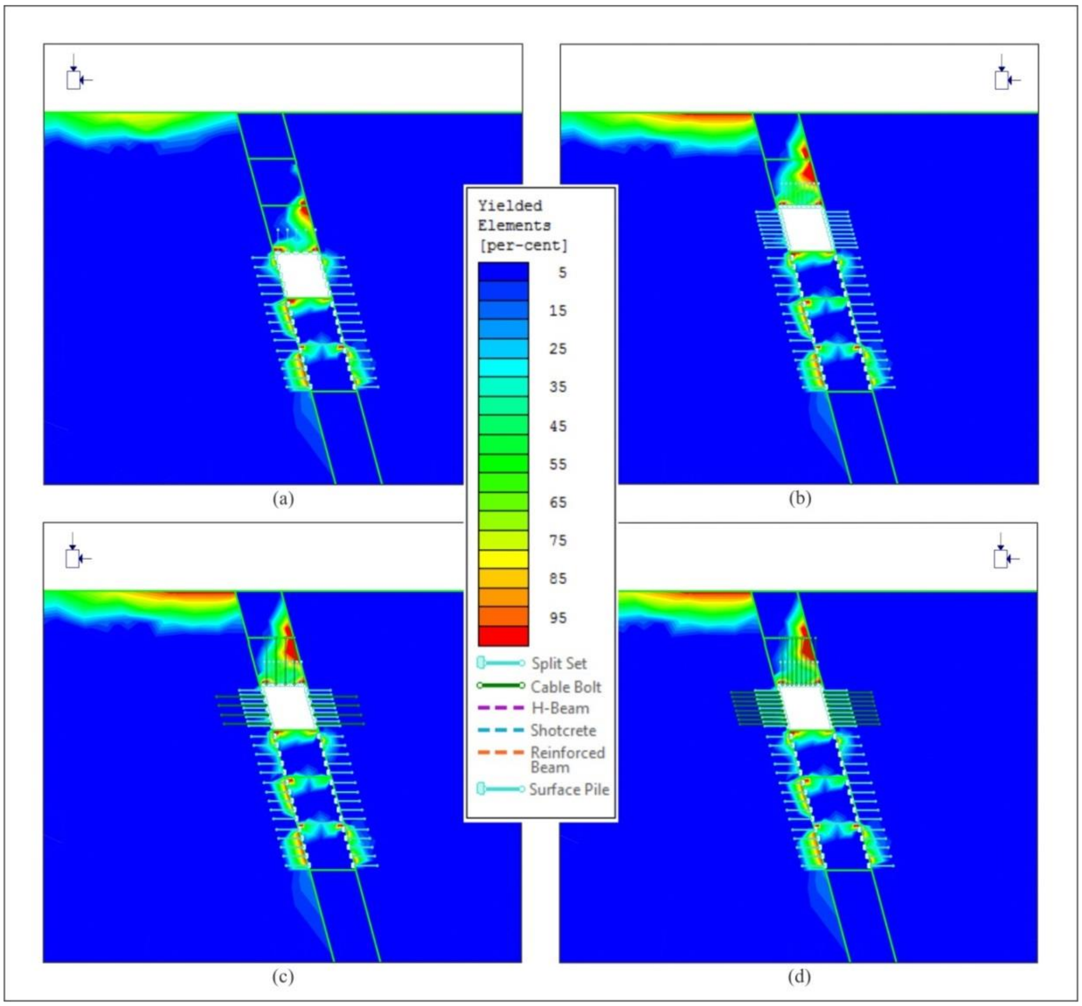

Figure 3.10 Simulation result of stope supported by the active type rock support for a model with stress ratio (k) 0.75.

3.3.2.3. Stress Ratio (k) 1.5

Simulation results for model with stress ratio 1 are similar to those in Section 3.3.1.3 due to similar stress ratio and rock mass parameter condition. This section reveals the effectiveness of rock support as countermeasure method when applied at stope in areas with a high horizontal stress value which is one and a half of its vertical stress value. The simulation results are given in Figure 3.11. Split set with 0.5 m x 0.5 m spacing can only support stope at the first slice (Figure 3.11(a)). The second slice cannot be executed by using the same split set design and even a combination of split set and cable bolt with tight spacing as revealed in Figures 3.11(b)-3.11(d). Unlike the simulation result for model with stress ratio below 1, active type rock support system is not capable to support stope in condition where high horizontal stress occurs around the stope area.

Passive type rock support is then installed from the second slice and the result is shown in Figure 3.12. The application of shotcrete is proven effective to stabilize stope from the second slice until the fourth slice as can be seen in Figures 3.12(a) and 3.12(b). Crown pillar failure occurs when the fifth slice is executed as shown in Figure 3.12(c). Shotcrete is yielded and 4.4 mm displacement occurs at the center of stope roof perimeter. Figure 3.12(d) shows H-beam also cannot give a proper supporting capacity for stope and crown pillar at fifth slice. Both displacement and yielded elements is not reduced significantly from the model supported by shotcrete. Therefore, the supporting design in Figure 3.12(b) is considered as an optimum design.

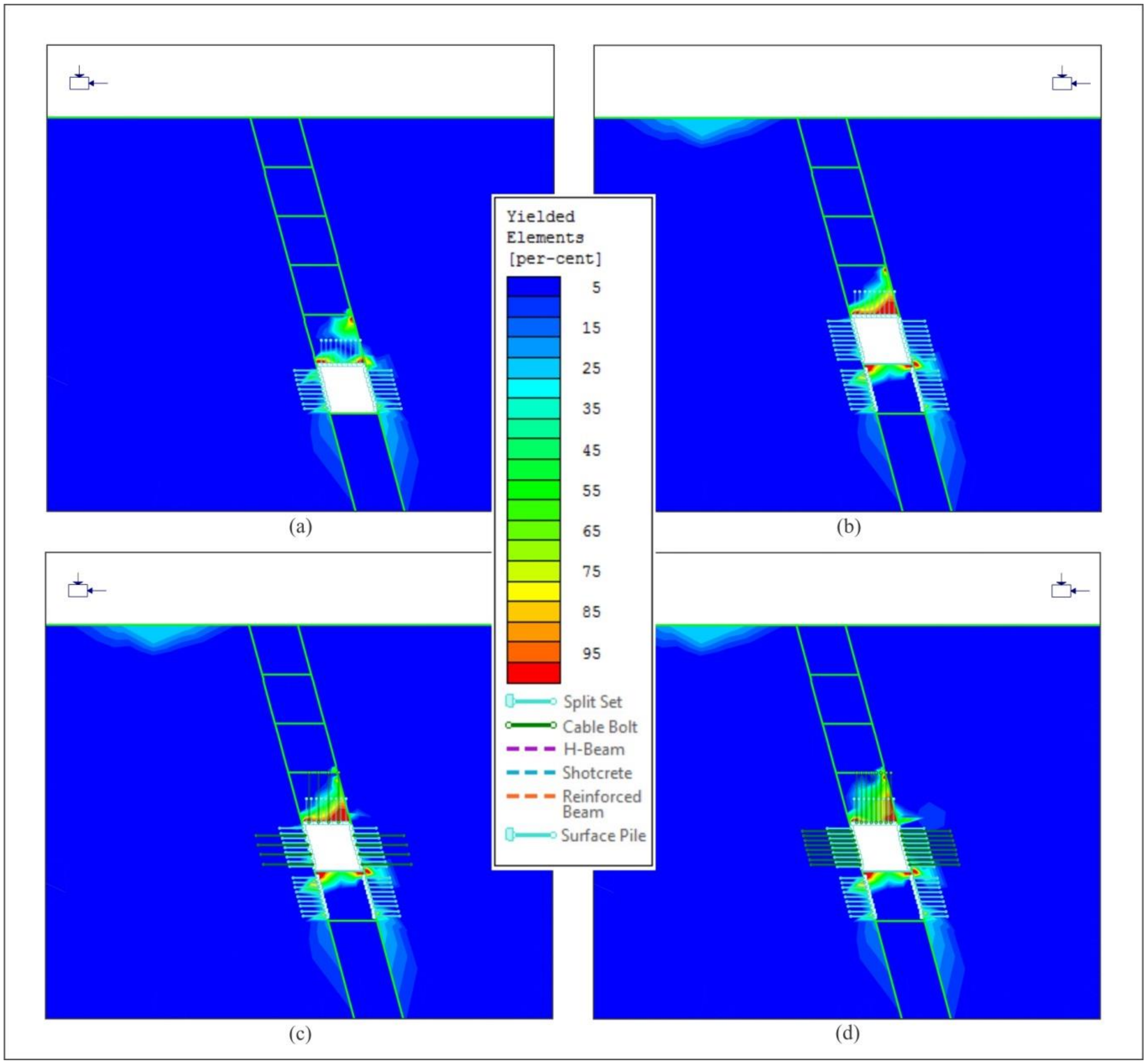

Figure 3.11 Simulation result of stope supported by the active type rock support for a model with stress ratio (k) 1.5.

3.3.2.4. Stress Ratio (k) 2

Simulation of model with stress ratio 2 is carried out in order to get a clearer trend on the effectiveness of rock support as countermeasure method for stope instability in high horizontal stress condition. Simulation results of stope supported by the active type rock support for model with stress ratio 2 are given in Figure 3.13. The result strengthens the previous statement that the application of the active type support system in this condition is not effective. Even the combination between cable bolt and split set with tight spacing, in Figures 3.13(c) and 3.13(d), cannot stabilize the stope at first slice. Failure not only occurs at stope but propagates until surface area.

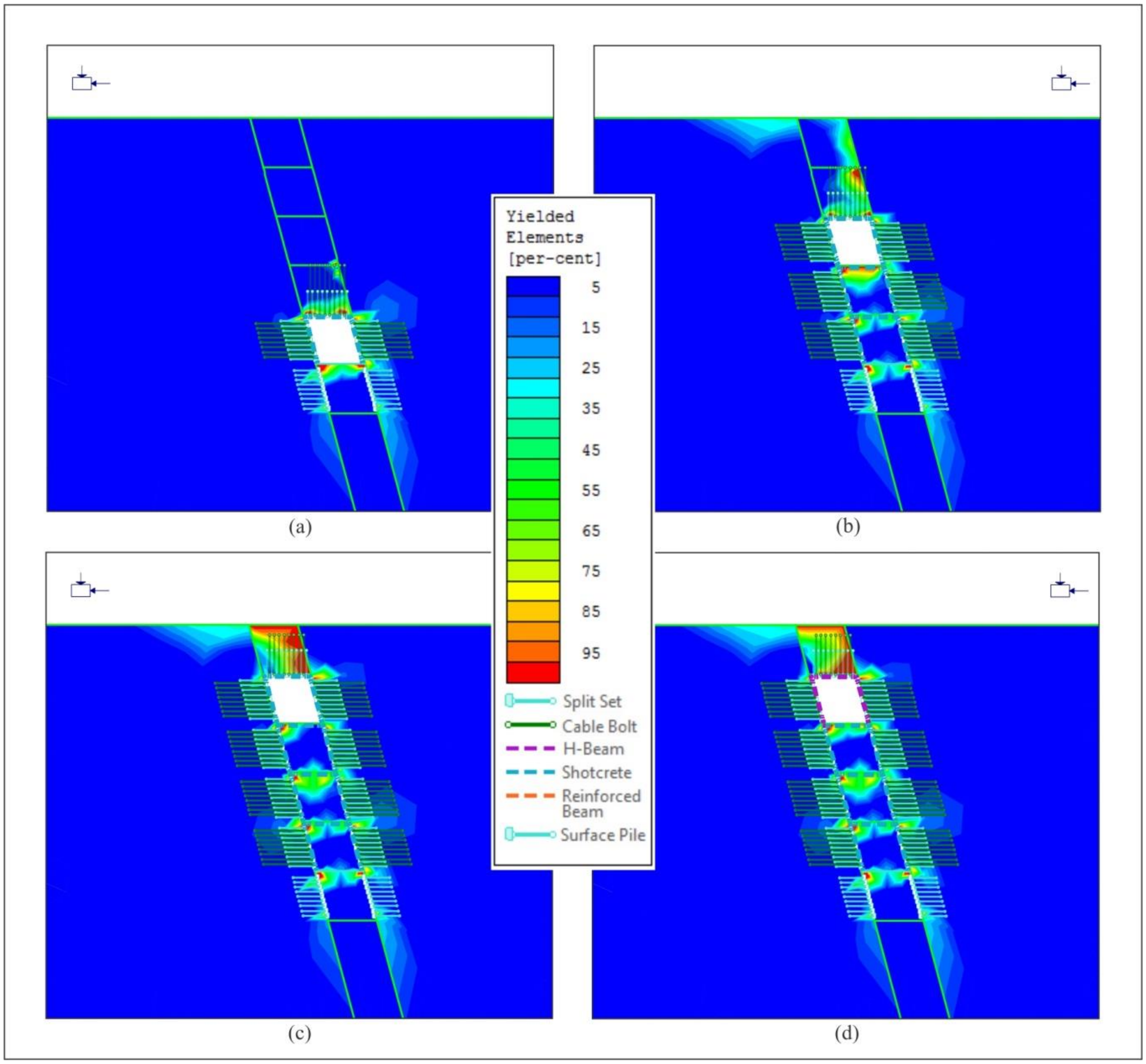

Figure 3.12 Simulation result of stope supported by the passive type rock support for a model with stress ratio (k) 1.5.

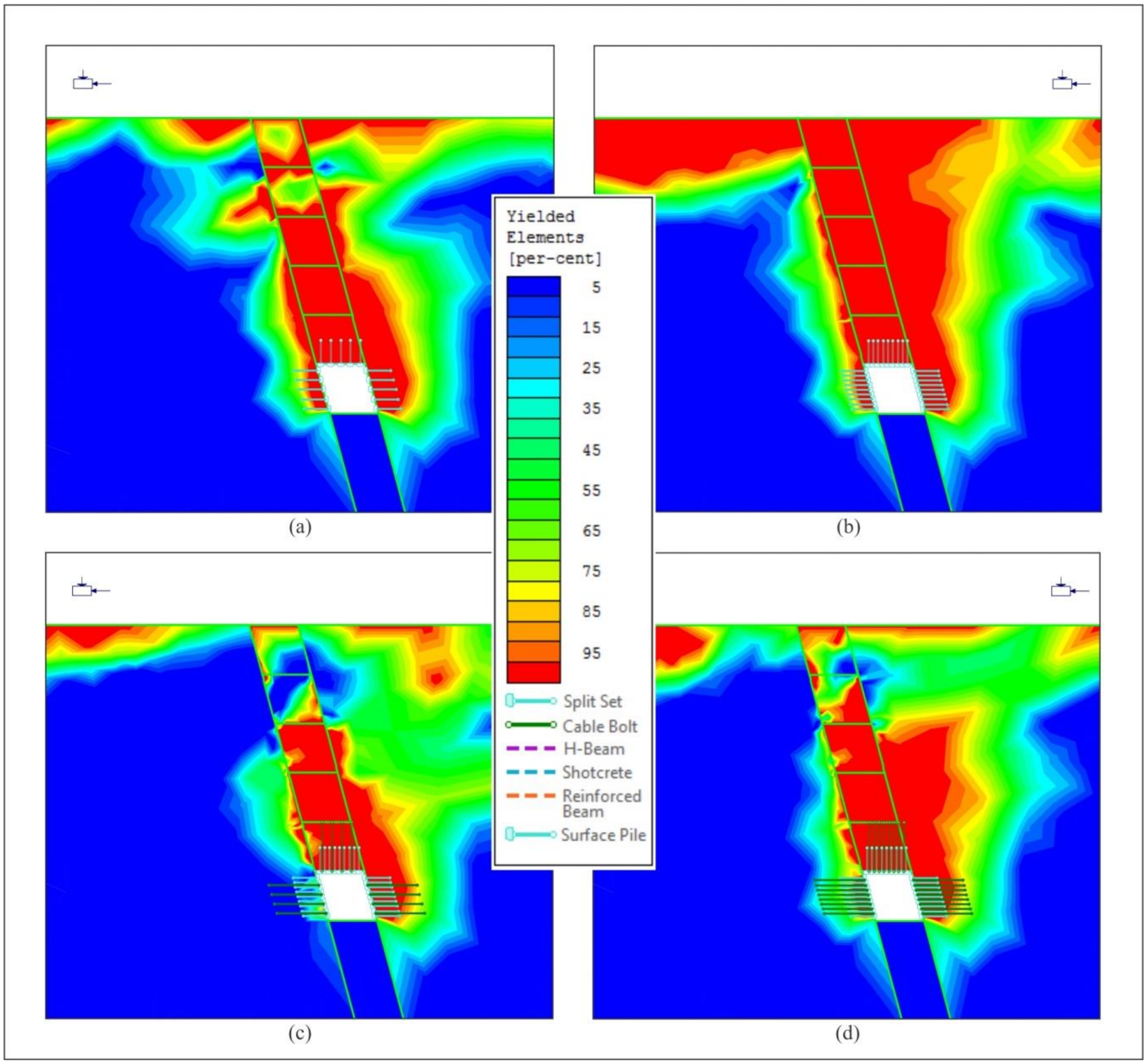

Figure 3.13. Simulation result of stope supported by the active type rock support for a model with stress ratio (k) 2.

Simulation results of passive type rock support installation in the model can be seen in Figure 3.14. Installation of shotcrete can support the stope at first slice as shown in Figure 3.14(a). However, as it is installed at second slice, failure of the roof occurs as can be seen in Figure 3.14(b). Only small displacement of 1.9 mm occurs at the center of stope roof perimeter but shotcrete is also yielded. Highest displacement occurs at the hanging wall side of the stope perimeter with 1.9 cm. Figure 3.14(c) shows the installation of H-beam can give a proper supporting capacity to stabilize the stope at second slice. Nevertheless, instability occurs when the H-beam is installed to support stope at third slice with several active type support yielded and 1.8 cm displacement recorded at the hanging wall side of the stope perimeter. Based on this analysis, mining should be stopped until the second slice and 20 m thickness of crown pillar need to be spared. The optimum rock support design for stope is the one shown by Figure 3.14(c).

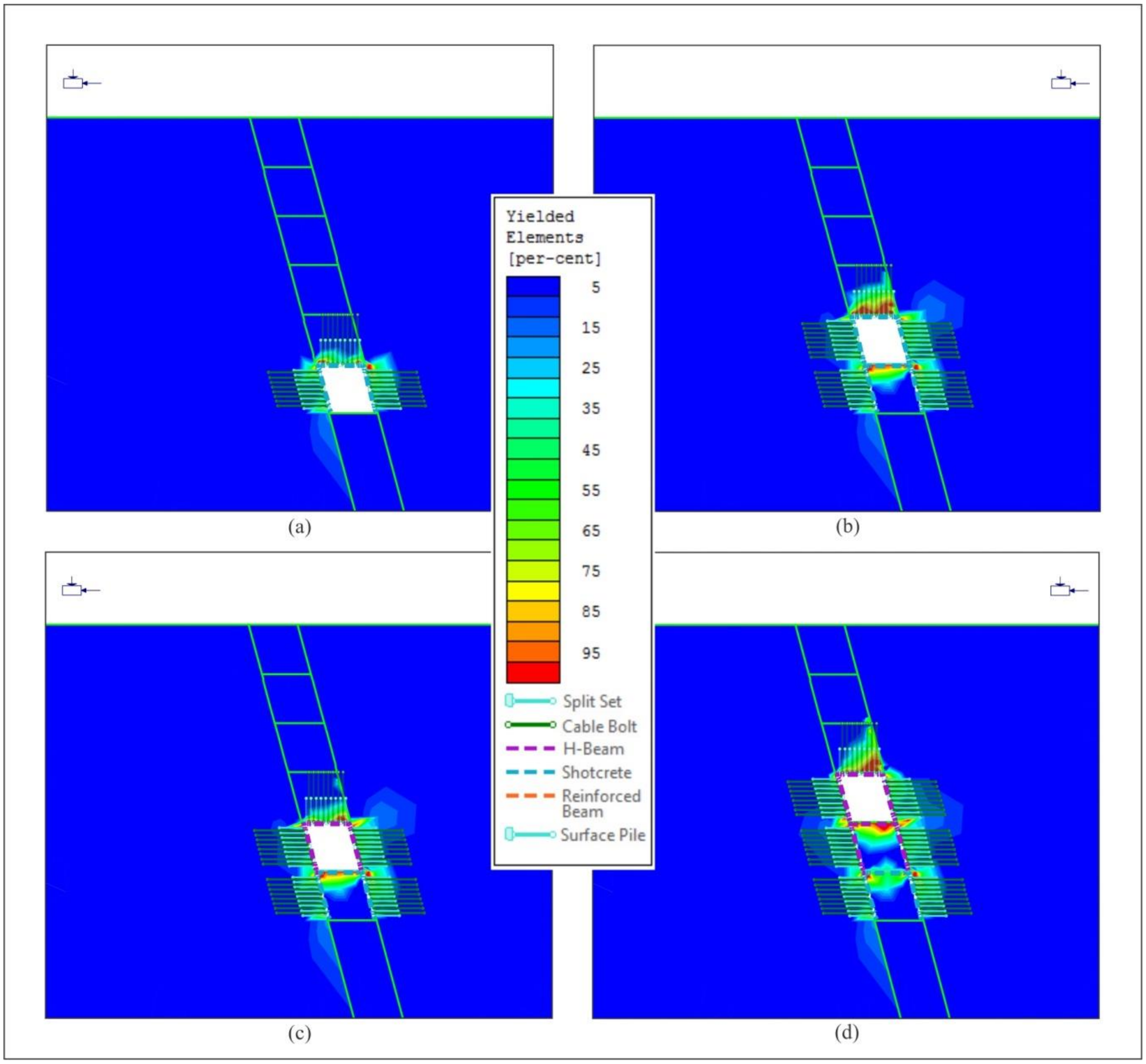

Figure 3.14 Simulation result of stope supported by the passive type rock support for a model with stress ratio (k) 2.

Rock support design as countermeasure for stope instability needs to adapt to the stress ratio condition within the mine. In a lower stress ratio condition, application of active type rock support is adequate and needs to be prioritized over the passive one. When mine is located at area with high stress ratio condition, passive type rock support needs to be installed. Higher supporting capacity is needed as the stress ratio becomes higher. Therefore, installation of passive type rock support such as H-beam needs to be considered when the stope is opened in mine with high stress ratio condition.

3.3.3. Parametric Study of Numerical Model with Different Vein Dip

Results in second chapter show that crown pillar failure is more likely to occur when stope opened at vein with low dip and special attention needs to be given on the hanging wall side. The effectiveness of active and passive rock support is evaluated in the model with different dip. The results will be explained in the following sections.

3.3.3.1. Vein Dip 50^o

In the previous analysis for model with various geological conditions and stress ratios, active type rock support in wall side of stope is installed in horizontal direction. Installation in horizontal direction for split set or cable bolt is common to be used in Indonesian cut and fill gold mine. Therefore, it is used as a pattern for installing active type rock support in previous analysis. However, after series of simulation for model with vein dip 50^o, it is found that the direction of active type rock support influences the crown pillar stability especially at the hanging wall side. Changing the direction of active type rock support at wall side of the stope might be needed to increase its supporting effect.

Results of simulation in Figure 3.15 show stope and crown pillar stability for model with vein dip 50^o where the stope is supported by both active and passive type rock support. The active type rock support in wall side of the stope is installed in horizontal direction. The results in this figure are focused in the crown pillar stability. It can be seen from Figure 3.15(a) when active type rock support i.e. split set is installed at the horizontal direction, crown pillar failure occur at a large scale extends into hanging wall zone. Addition of cable bolt in 0.5 m x 0.5 m spacing gives better yield condition but still indicates crown pillar failure as can be seen in Figure 3.15(b). Moreover, addition of passive type rock support as can be seen in Figure 3.15(c) and 3.15(d) shows no significant improvement to the crown pillar stability.

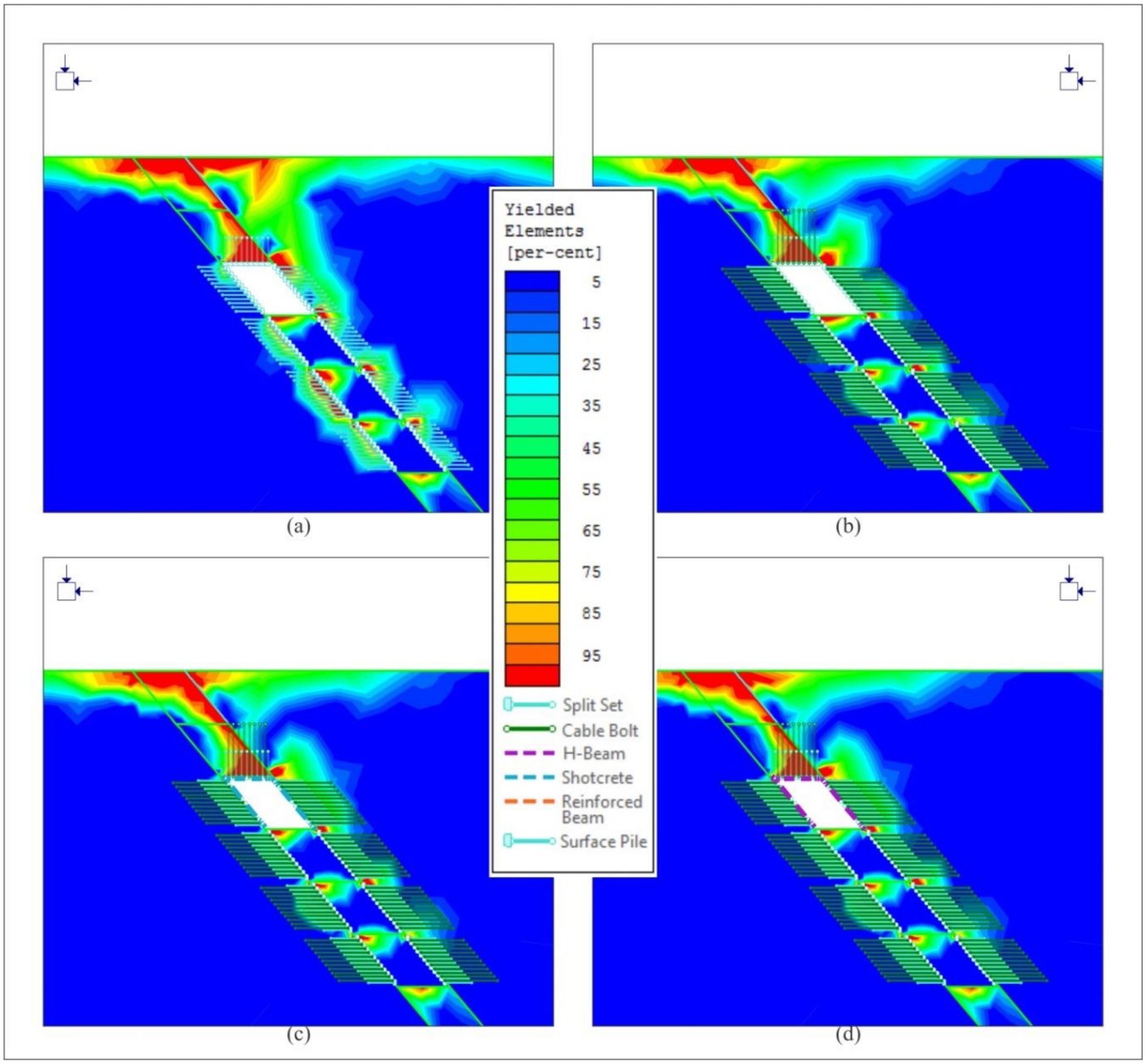

Figure 3.15 Simulation result of stope supported by rock support where active type in the wall side of the stope is installed in horizontal direction.

Modification of active type rock support direction is made. In the next simulation, the active type rock support is installed in normal direction to the wall side perimeter of stope. The simulation results are given in Figure 3.16.

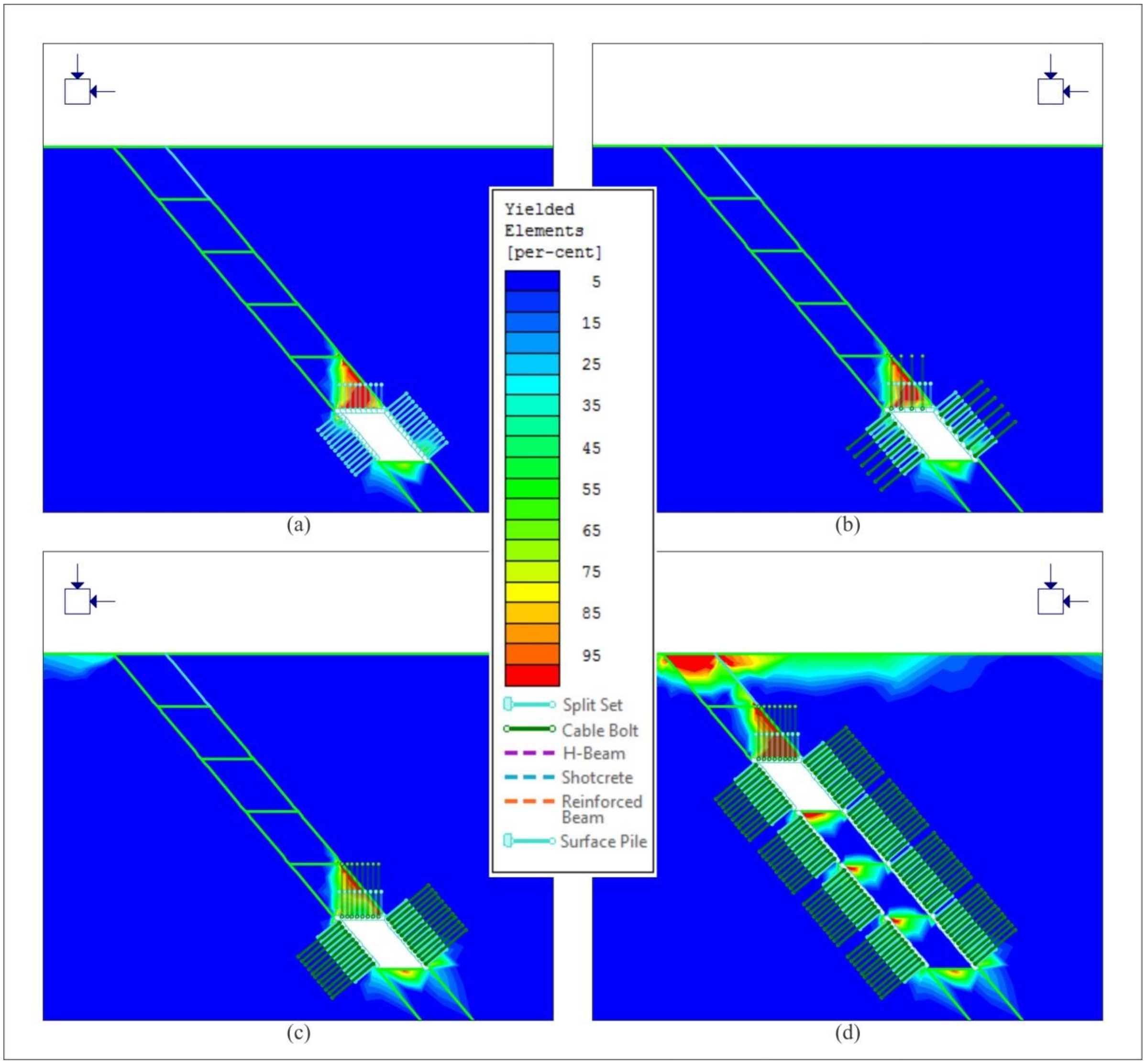

Figure 3.16. Simulation result of stope supported by the active type rock support where the one in wall side of the stope is installed in normal direction.

For the stope stability, both split set with 0.5 m x 0.5 m spacing (Figure 3.16(a)) and combination of split set with 0.5 m x 0.5 m spacing and cable bolt with 1 m x 1 m spacing (Figure 3.16(b)) cannot stabilize the stope at the first slice. Yield zone, dominated by the fully yielded zone (100% yielding shown in red color), with the arch shape occurs above the stope. When cable bolt spacing is increased into 0.5 m x 0.5 m in Figure 3.16(c), the arch shape above the stope still occurs but the fully yielded zone is reduced and not forming an arch shape anymore. Moreover, displacement at the center of stope roof perimeter decreases from

9.1 mm in the simulation result of model shown in Figure 3.16(a) into 7.2 mm. Therefore the condition shown in Figure 3.16(c) can be considered as stable. Simulation result shows that the execution of the second and third slices by using the same rock support system is in the similar condition. Failure in a relatively same condition with the Figures 3.16(a) and 3.16(b) was found in Figure 3.16(d) or at the fourth slice.Compared with the result in Figure 3.15(b), crown pillar stability in Figure 3.16(d) is better. Excavation of the fourth slice in Figure 3.16(d) did not cause crown pillar in the hanging wall zone to collapse. Thus it is worth to mention that the direction of active type rock support in the wall side of the stope has influence on crown pillar stability especially if the stope is opened at vein with low dip. By changing the direction of active type rock support from horizontal into normal direction of wall side perimeter of the stope, the unsupported area of hanging wall zone around the stope becomes smaller. As the result, the active type rock support becomes more effective in supporting the hanging wall area.

Simulation result in Figure 3.16(d) shows crown pillar stability at hanging wall zone improves but the stope and crown pillar at fourth slice is still failure. Optimization of crown pillar thickness is carried out by installing passive type rock support. The results are summarized in Figure 3.17.

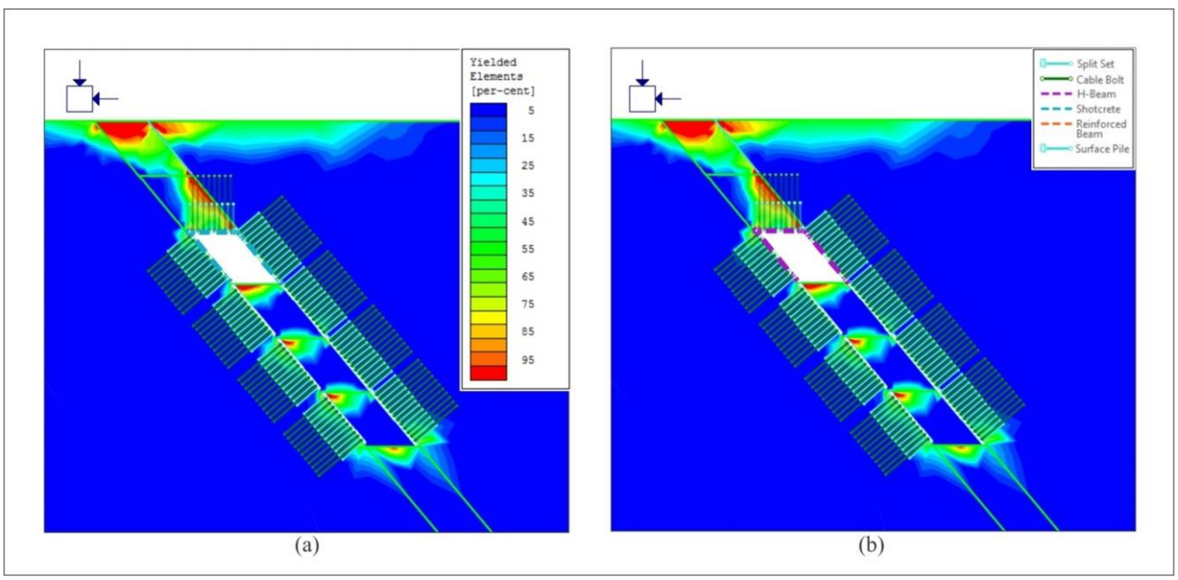

Figure 3.17 Simulation result of stope supported by the passive type rock support for a model with vein dip 50^o.

Significant improvement on fully yielded zone is made by installing shotcrete at the fourth slice (Figure 3.17(a)). However, yielded zone pattern suggests crown pillar failure occurs. Replacing the shotcrete with H-beam as shown in Figure 3.17(b) also cannot prevent the crown pillar failure at the fourth slice.

3.3.3.2. Vein Dip 62.5°

Having steeper dip than previous model, model with vein dip 62.5° needs less quantity of rock support than the model with vein dip 50°. The first slice is in stable condition after supported by split set with 0.5 m x 0.5 m split set as shown in Figure 3.18(a). Yielded zone form an arch shape but there are almost no occurrences of fully yielded zone. The second slice until the fourth slice need to be supported by the combination of split set and cable bolt with 0.5 m x 0.5 m spacing (Figure 3.18(c)). The 5 m thickness crown pillar cannot be supported by using the same rock support design as can be seen in Figure 3.18(d).

The passive type rock support which is shotcrete is installed to support both stope and crown pillar at the fifth slice. The result is shown in Figure 3.19. The stability of crown pillar improves with installation of shotcrete. The yield zone is not continuous until the stope. Therefore crown pillar can be considered as stable by using the rock support design shown in Figure 3.19. Simulation result for model with vein dip 75° is not discussed since the result is same with the one in Section 3.3.1.3. By comparing rock support design from those three models, it can be concluded that the amount of rock support needed to support stope decreases as the stope is excavated in steeper dip.

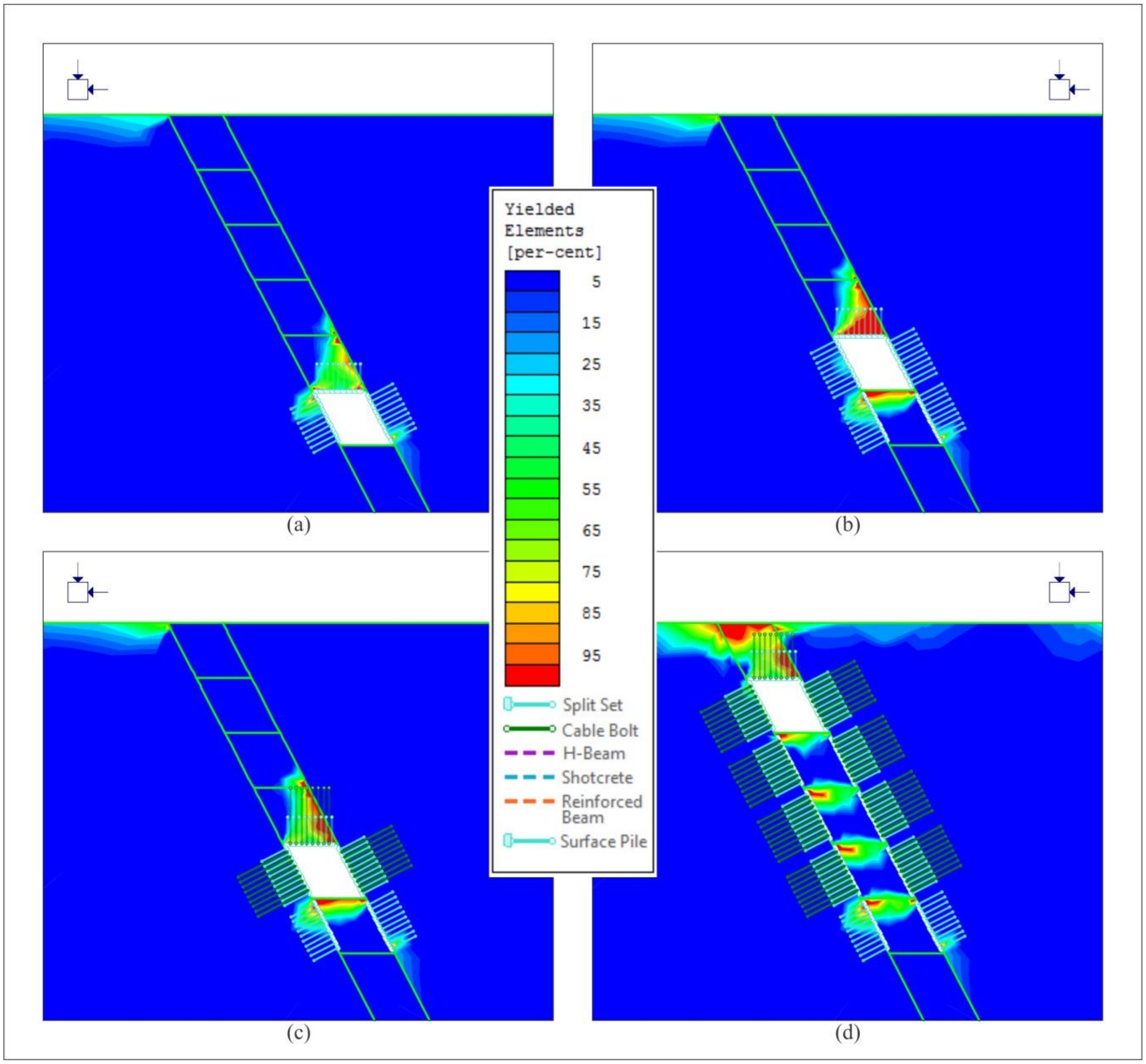

Figure 3.18 Simulation result of stope supported by the active type rock support for a model with vein dip 62.5°.

From all of simulation results for different vein dip, stoping in lower vein dip needs more rock support to be installed at the stope. Therefore, when the ore vein dip changes during stoping, it is important to evaluate the rock support design. Moreover, if the ore vein dip is low, it is better to install the active type rock support in normal direction of the stope perimeter to prevent crown pillar failure at hanging wall area.

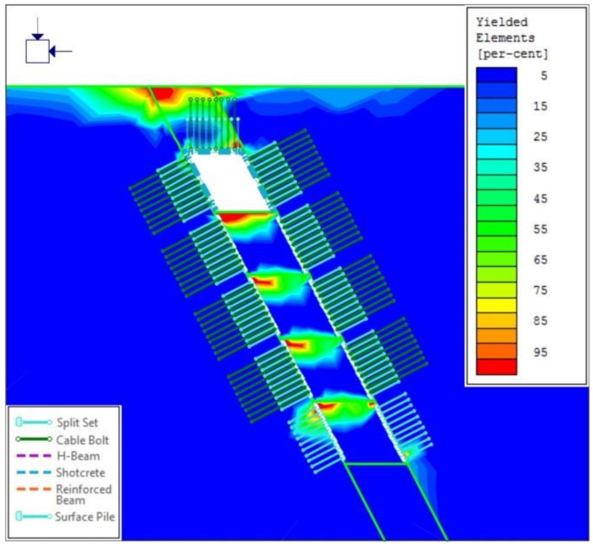

Figure 3.19 Simulation result of stope supported by the passive type rock support system for a model with vein dip 62.5^{o}.

3.3.4. Parametric Study of Numerical Model with Different Vein Width

With the increasing differential stress value as the stope becomes wider, it is expected that the quantity of rock support needed to stabilize stope and crown pillar increases as the stope width increases. Two additional models with different width, apart from model with vein width of 5 m that already discussed in Section 3.3.1.3, are simulated with active and passive type rock support installed at the stope. The results are discussed in the following sections.

3.3.4.1. Vein Width of 3.75 m

Model with vein width of 3.75 m does not require rock support as much as model with vein width of 5 m as shown in Section 3.3.1.3. Split set with 1 m x 1 m spacing can support the first slice as shown in Figure 3.20(a). Further analysis in the second slice shows that the same support design can be used to stabilize stope. Failure occurs when the stope at third slice is supported by the split set with 1 m x 1 m spacing (Figure 3.20(b)). Tighter spacing needs to be applied at the third slice as can be seen in Figure 3.20(c). The simulation is continued for the fourth and fifth slice. It is found that the fourth slice is in stable condition. Looking closer to the pattern shown from simulation result of fifth slice in Figure 3.20(d), the yield zone above the stope is not continuous until the surface. Moreover, there is only small occurrence of fully yielded zone at crown pillar rock mass. Therefore, it is more likely that crown pillar is in stable condition.

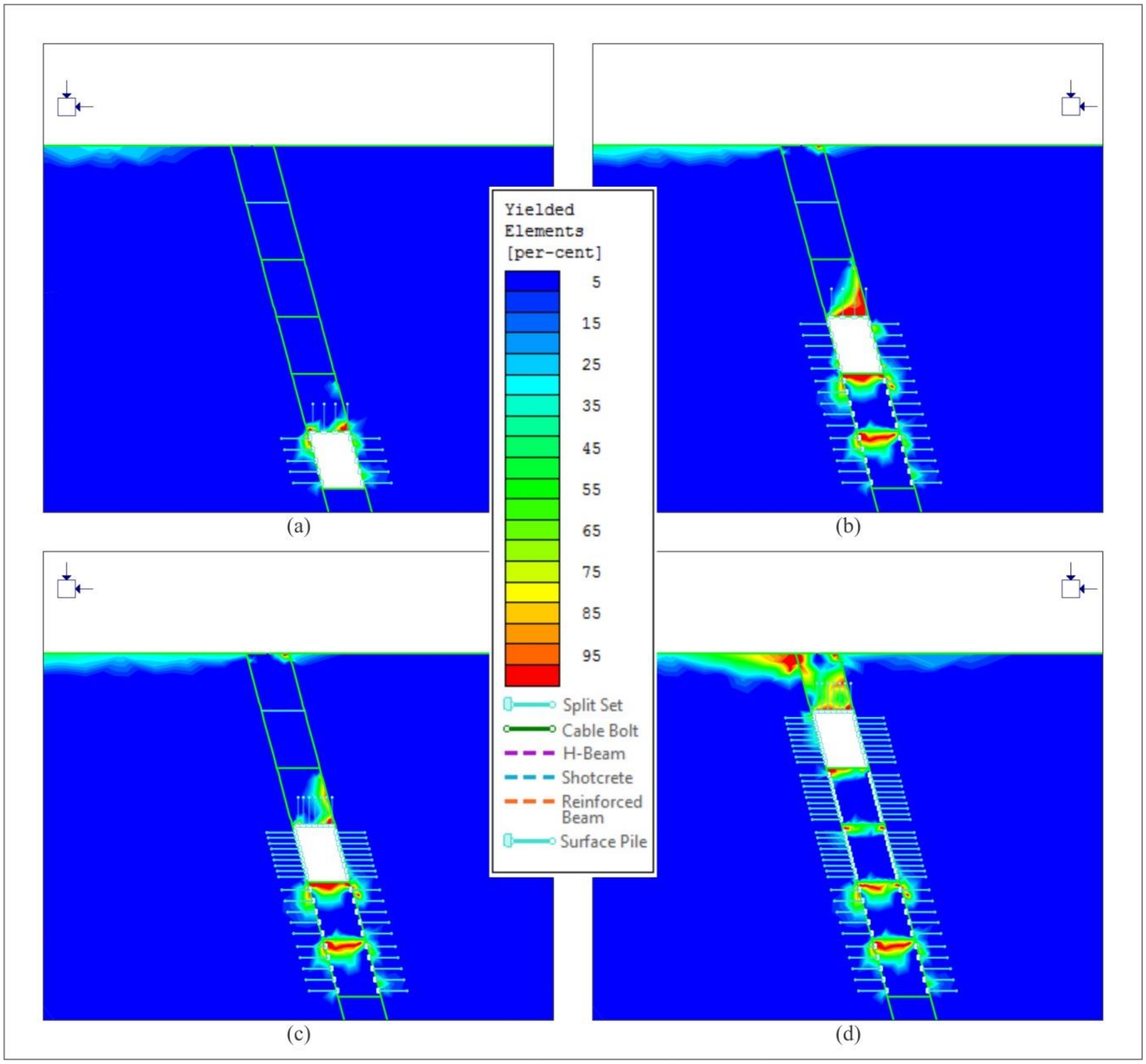

Figure 3.20 Simulation result of stope supported by the active type rock support for a model with vein width of 3.75 m.

3.3.4.2. Vein Width of 6.25 m

Being the model with the widest vein width compares with the other two models, the model with vein width of 6.25 m needs more quantity of rock support as can be seen from the results of simulation given in Figure 3.21.

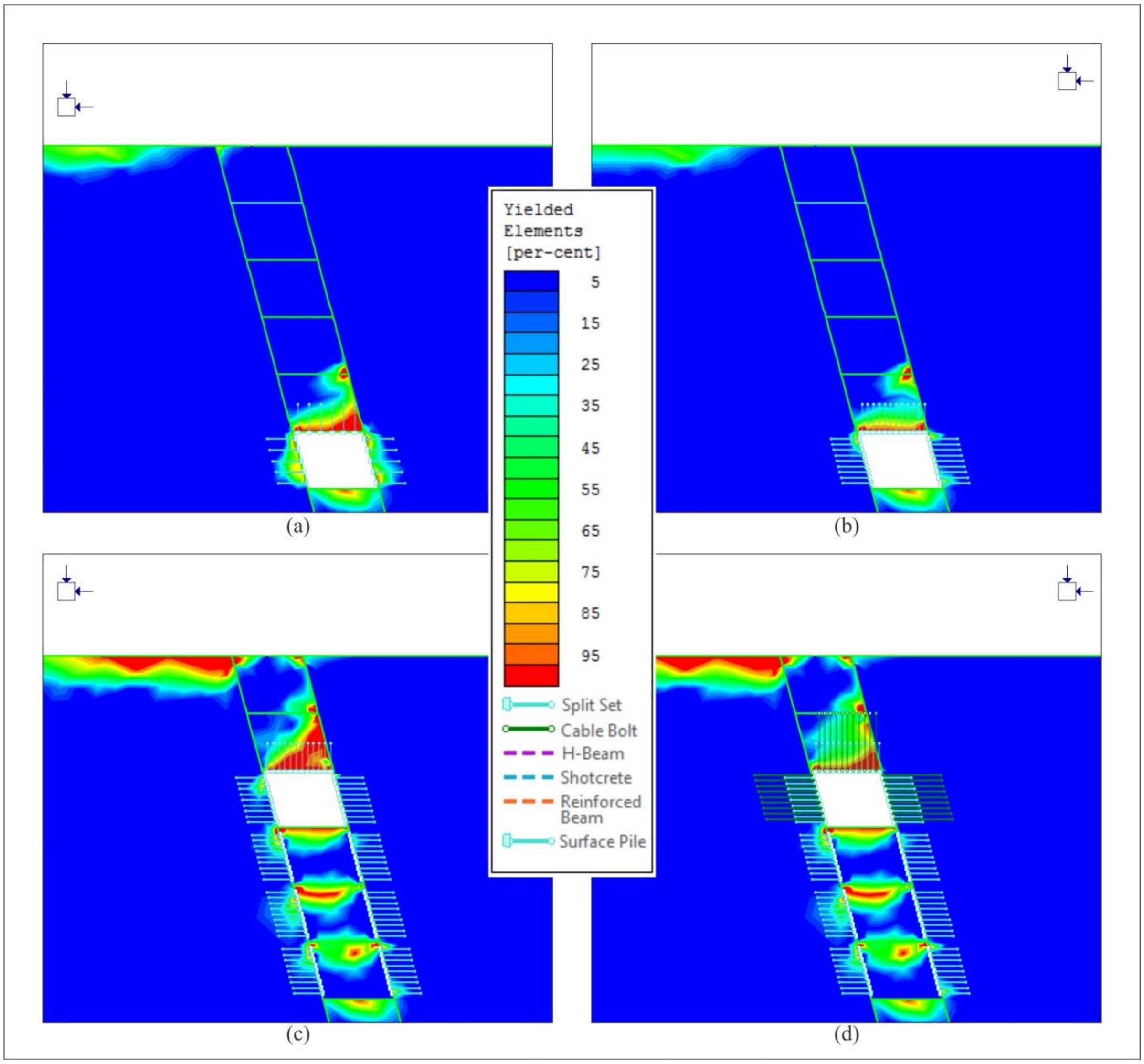

Figure 3.21 Simulation result of stope supported by the active type rock support for a model with vein width of 6.25 m.

In models with vein width of 3.75 m and 5 m, stope at the first slice can be supported by split set with 1 m x 1 m spacing. Only in the model with vein width of 6.25 m, stope failure occurs when first slice is supported by split set with 1 m x 1 m spacing as can be seen in Figure 3.21(a). Split set with tighter spacing, which is 0.5 m x 0.5 m, is needed to stabilize the stope at first slice as shown in Figure 3.21(b). Failure with the same rock support design occurs when the fourth slice is excavated (Figure 3.21(c)). Addition of cable bolt with 0.5 m x 0.5 m cannot stabilize the fourth slice as can be seen in the Figure 3.21(d).

An effort to maximize crown pillar recovery is carried out by installing passive type rock support and the results are given in Figure 3.22. Addition of shotcrete can stabilize the fourth slice from collapse as shown in Figure 3.22(a). However, it still cannot stabilize the next slice which is the fifth slice (Figure 3.22(b)). The installation of H-beam instead of shotcrete in the fifth slice cannot stabilize the stope and crown pillar. Therefore, the optimum rock support design is the one shown in Figure 3.22(a). 10 m thickness crown pillar needs to be spare to maintain crown pillar stability.

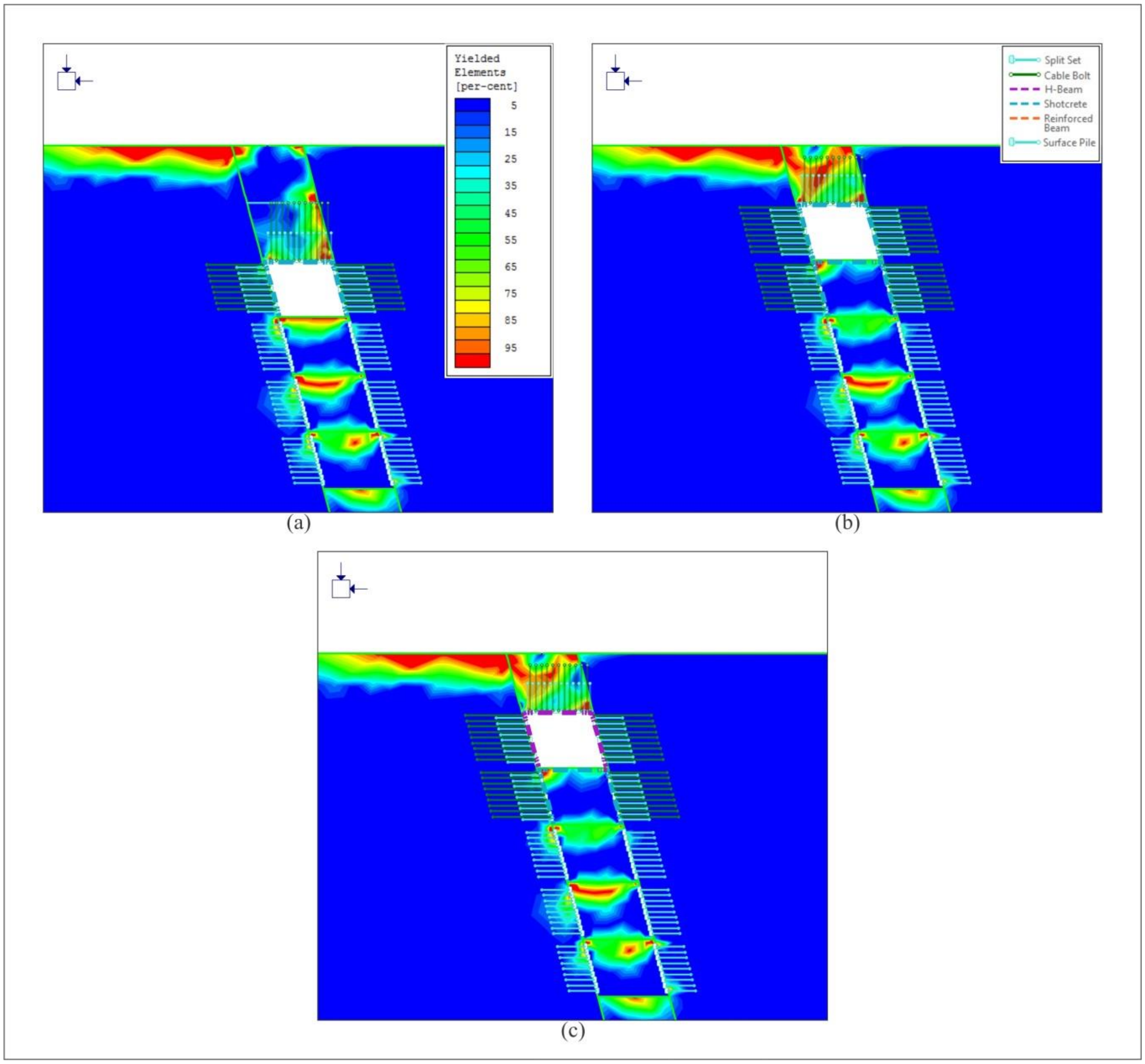

Figure 3.22 Simulation result of stope supported by the passive type rock support for a model with vein width of 6.25 m.

For rock support design in different vein width, reduction of rock support can be carried out when the ore vein width becomes smaller. On the contrary, if the ore vein width becomes larger, more active type rock support or even passive one needs to be installed at the stope. Special attention needs to be given on the stope roof since it becomes more unstable as the span increase.

3.4. Conclusion

Effectiveness of active and passive type rock support as countermeasure for stope instability near crown pillar area has been investigated by means of parametric study. In general, more supporting capacity of both types support system are needed if the stope is opened in more severe geological condition, higher stress ratio, lower vein dip and wider vein width. Moreover, the result shows active type support system is not effective for supporting stopes in case the ratio of horizontal stress to vertical stress larger than 1 because the large failure zone is developed in the roof. Therefore, the passive type support should also be installed in the stopes in order to maintain the stability of stope and crown pillar if the stope is excavated at high horizontal stress conditions. Simulation results of model with different vein width show that the direction of active type rock support in the wall side of stope perimeter has influence on crown pillar stability especially at hanging wall area.

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Thompson, A. and Windsor, C.R. (1993) Theory and Strategy for Monitoring the Performance of Rock Reinforcement. Proceedings Geotechnical Instrumentation and Monitoring in Open Pit and Underground Mining, Balkema, Rotterdam, 473–482.

Chapter 4

Sill Pillar Application to Maximize Crown Pillar Recovery in Overhand Cut and Fill Underground Mine

The effectiveness of active and passive type rock support as countermeasure for stope instability in crown pillar area has been investigated in the third chapter. As a common method for stabilizing underground opening, application of rock support is proven effective to support stope and also crown pillar in various mine conditions simulated in previous chapter. Moreover, crown pillar recovery can be maximized by applying combination of both passive and active type rock support. However, at several cases of overhand cut and fill analyzed in the third chapter, a thick crown pillar still needs to be spared to prevent crown pillar failure that may cause subsidence. Some of the examples are crown pillar for model with GSI 37.5 where minimum crown pillar thickness is 15 m and model with stress ratio 2 where minimum crown pillar thickness is 20 m.

In several mines, ore located at the higher level or near surface contains higher grade than ore at the lower level. Pongkor gold mine, as an example, has relatively higher grade ore (> 30 ppm Au) in near surface area for Kubang Cicau and Ciurug Vein (Basuki et al., 1994). Therefore, it is important to optimize the crown pillar recovery by minimize crown pillar thickness as much as possible to maximize the benefit from natural resources development at protected forest. Nevertheless, this optimization must be carried out with the high awareness of the need to maintain the stability of crown pillar to prevent subsidence.

Sill pillar application to maximize crown pillar recovery will be introduced in this chapter. It will reduce the accumulation of induced stress at stope and crown pillar thus increase their stability. An attempt has been made to understand the effectiveness of sill pillar to maximize crown pillar recovery as well as to stabilize stope and crown pillar. The result will be given in the following sections.

4.1. Schematic of Sill Pillar for Crown Pillar Optimization

Sill pillar is defined as portion of deposit underlying an excavation and left in place as a pillar (Gregory, 1980; Hamrin, 1982; American Geological Institute, 1997). In overhand cut and fill mining, sill pillar usually formed due to operational reason. Application of hydraulic fill may halt the production due to the need to wait curing time before the next slice above it can be excavated. As a consequence, stope at several different levels needs to be opened to maintain the production continuity. By doing so, production can be continued at stope in different level while waiting for the backfilled stope to completely cured. As the stoping progressing upwards, the group of stope which starts from lower level will get close to the group of stope which starts from upper level. Both of the group will be separated by sill pillar as can be seen in Figure 4.1. Another reason to leave a sill pillar is to have a higher production level. To achieve this purpose, several groups of stope will be opened in different level at the same time so that higher production level will be achieved.

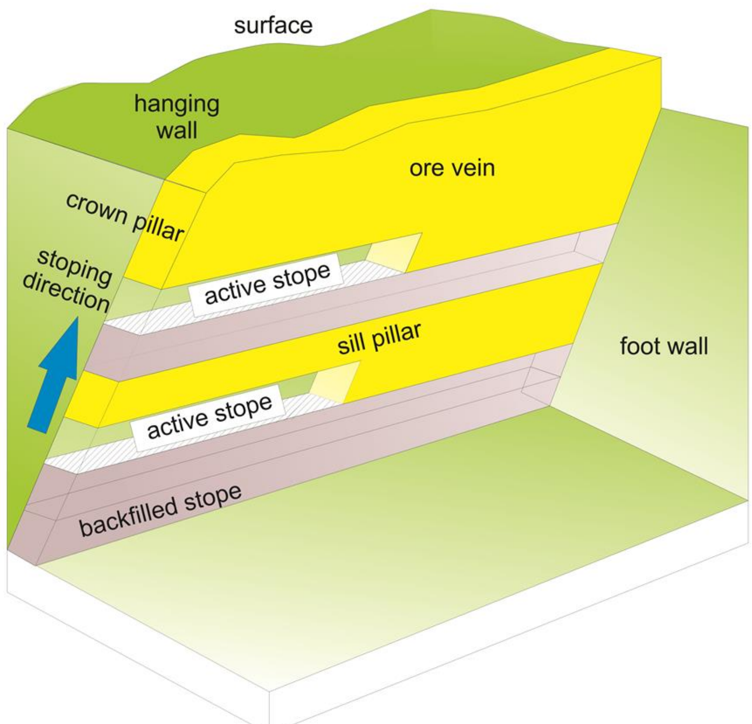

Figure 4.1. Schematic of sill pillar in overhand cut and fill underground mining method.

In this chapter, sill pillar will be introduced as an alternative countermeasure for stope instability and to maximize crown pillar recovery. Applying sill pillar for this purpose can be carried out by abandon uppermost unstable slice from the simulation of stope supported by rock support as a sill pillar. Stoping will be continued above the abandoned slice. Schematic of sill pillar application for crown pillar optimization is shown in Figure 4.2. The schematic shown in Figure 4.2 is schematic of sill pillar application to optimize crown pillar in model with GSI 37.5 where it is found in Section 3.3.1.2 that stope failure at the fourth slice cannot be prevented even by installation of H-beam. Therefore, the fourth slice is abandoned as sill pillar and stoping is continued above it. The result of simulation will be discussed in the following sections along with the application of sill pillar in other different models.

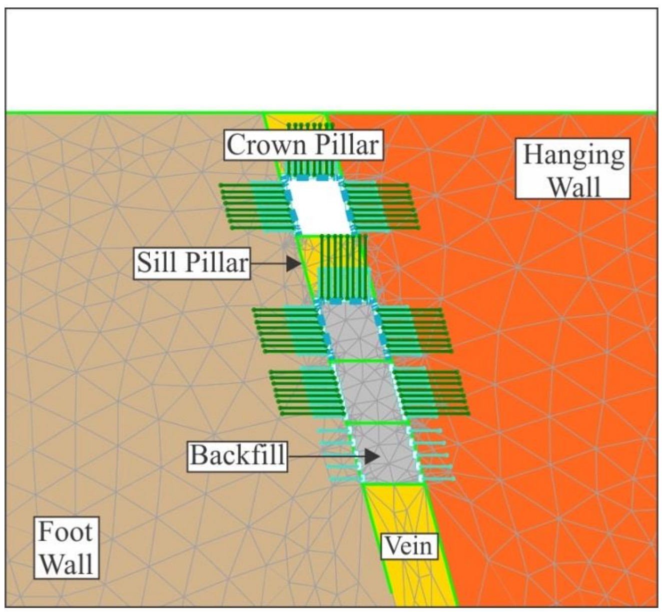

Figure 4.2. Schematic of sill pillar application for crown pillar optimization.

4.2. Sill Pillar Application to Maximize Crown Pillar in Various Mine Conditions

4.2.1. Sill Pillar Application in Model with GSI 37.5

The minimum crown pillar thickness from simulation of stope supported by rock support for model with GSI 37.5 is 15 m. The fourth slice is unstable even after supported by H-beam. To maximize the crown pillar recovery using sill pillar, the same model, which has 5 m width vein dipping in 75^o, with the same rock mass properties is used for simulation. Rock support design for the first until the third slices is similar to the one in Section 3.3.1.2. The fourth slice is left behind as a sill pillar and the slice above it is excavated. The simulation result is given in Figure 4.3. The figure shows the occurrence of yielded zone at the surface. However, the yielded zone does not continue to the stope or isolated. Therefore, it can be interpreted that crown pillar is in stable condition. By applying sill pillar, another slice can be mined in the crown pillar area which means optimization of crown pillar recovery is achieved.

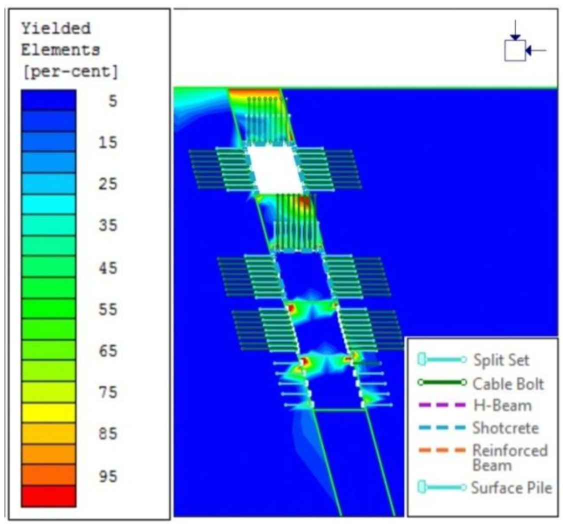

Figure 4.3. The effect of sill pillar to stope and crown pillar stability for a model with GSI 37.5.

Figure 4.4 shows the difference of stress distribution around stope and crown pilar for model with and without sill pillar. It is clear from the model without sill pillar in Figure 4.4(a) that induced stress from the first slice until the fourth slice will be accumulated forming large induced stress of group consists of four stopes. When sill pillar is applied (Figure 4.4(b)), the induced stress at the roof of the uppermost stope will be dominated by induced stress from the uppermost stope itself and relatively independent from induced stress of previous three stopes. This condition makes the stress at roof and crown pillar area lower than condition when sill pillar is not applied. From this result, it can be conclude that one of the effects of sill pillar application is reducing the accumulation of induced stress at the roof of uppermost stope and crown pillar area.

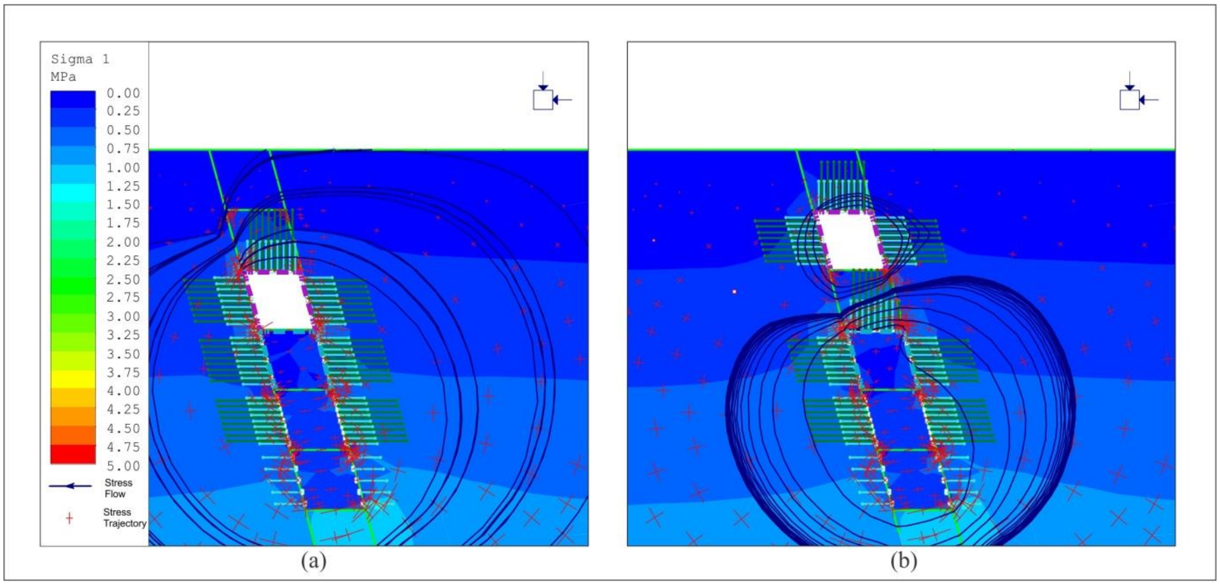

Figure 4.4. Effect of sill pillar on stress distribution around stope and crown pillar for a model with GSI 37.5.

4.2.2. Sill Pillar Application in Model with Different Stress Ratio (k)

Sill pillar application in different stress ratio condition will be evaluated at some model with different stress ratio in which crown pillar still possible to be optimized. The first simulation is carried out for model with stress ratio 0.5. If it is only rock support that being considered as a countermeasure method for stope and crown pillar instability in model with stress ratio 0.5, 15 m crown pillar thickness need to be spared based on simulation result in Section 3.3.2.1. To minimize it, additional simulation by making the fourth slice as sill pillar was carried out. The simulation result for stope above sill pillar and crown pillar stability is provided in Figure 4.5. It can be seen that both stope and crown pillar is in stable condition. Minimum crown pillar thickness with the application of sill pillar is 5 m with one abandoned slice, the fourth slice. Without sill pillar, mining should be stopped until the third slice. Application of sill pillar gives an additional one slice to increase crown pillar recovery.

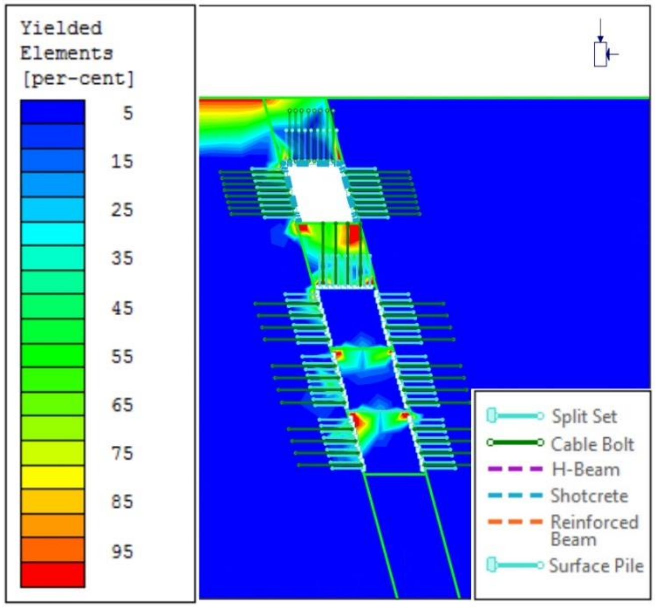

Figure 4.5. The effect of sill pillar to stope and crown pillar stability for a model with stress ratio (k) 0.5.

To understand the reason behind improvement that made by sill pillar application in Figure 4.5, stress distribution around stope and crown pilar for model with and without sill pillar is given in Figure 4.6. Before stoping is carried out, stress in the model is flowing in vertical direction due to stress ratio throughout the model is 0.5. When the stope is opened, induced stress around the stope occur and accumulated around roof of the uppermost stope and crown pillar as can be seen in Figure 4.6(a). The concentration becomes higher as the number of stope becomes higher as well. By applying sill pillar as shown in Figure 4.6(b), induced stress of the previous three stopes will be concentrated at uppermost stope roof of the first three stopes or at the sill pillar. It will not concentrated at crown pillar or stope above sill pillar. Induced stress at crown pillar area will be dominated by induced stress from the last stope above sill pillar that makes the stress at crown pillar lower than if sill pillar is not applied.

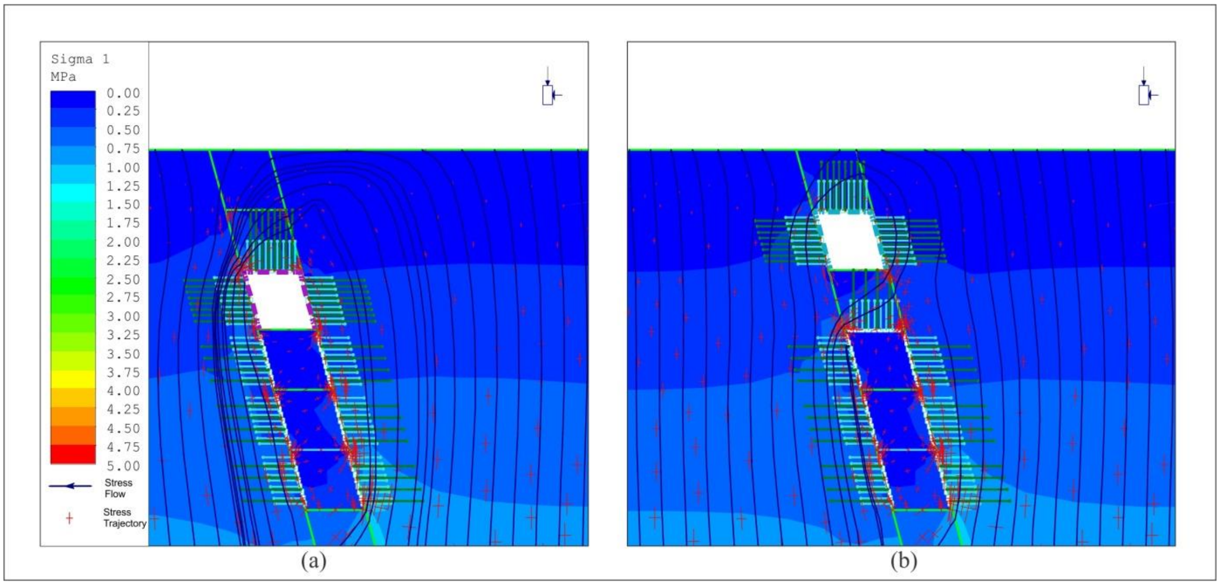

Figure 4.6. Effect of sill pillar on stress distribution around stope and crown pillar for a model with stress ratio 0.5.

Simulation results in Section 3.3.2.2 also show that passive type rock support cannot stabilize stope at fourth slice and crown pillar in the model with stress ratio 0.75. This model has similar stress condition with previous model where the vertical stress is higher than horizontal stress. Sill pillar is applied to maximize crown pillar recovery and the fifth slice is supported by using the same rock support design used in the fourth slice. The result is shown in Figure 4.7. Both stope and crown pillar can be considered as stable since the yield zone at the surface did not continue to the stope. This result along with the result in Figure 4.5 suggest that sill pillar application to maximize crown pillar recovery at mine where vertical stress is higher than the horizontal stress is effective. The stress distribution of model with and without sill pillar is relatively similar to the one in Figure 4.6 since vertical stress is higher than horizontal stress in both models. Therefore, the effect of sill pillar application is also similar to the one already explained previously.

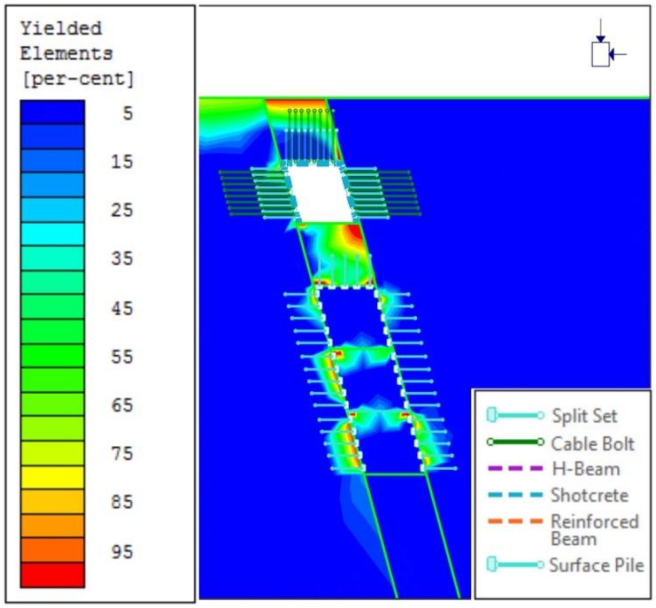

Figure 4.7. The effect of sill pillar to stope and crown pillar stability for a model with stress ratio (k) 0.75.

Previous simulations show that sill pillar is effective to optimize crown pillar in condition where vertical stress is higher than horizontal one. To evaluate its effectiveness in condition where horizontal stress is higher, crown pillar optimization by using sill pillar was carried out for model with stress ratio 2 that needs to spare the thickest crown pillar which is 20 m. Active type rock support and H-beam can only stabilize the stope at second slice. The same rock support design cannot be applied at the third slice so that stoping needs to be stopped at the second slice leaving 20 m thickness crown pillar.

To minimize crown pillar thickness, the third slice is abandoned as a sill pillar and the result shown in Figure 4.8. It can be seen that stope at fourth and even fifth slice is in stable condition as presented in Figures 4.8(a) and 4.8(b). The crown pillar is also in stable condition. Therefore, it can be concluded that application of sill pillar as an alternative countermeasure is also very effective for stope located in high horizontal stress area.

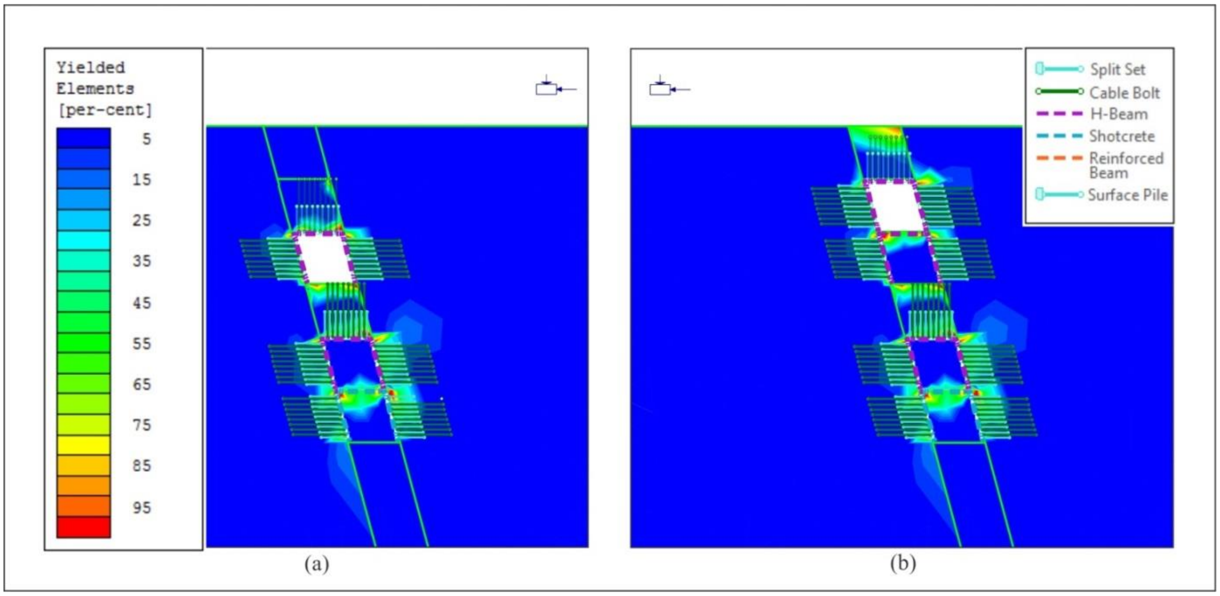

Figure 4.8. The effect of sill pillar to stope and crown pillar stability for a model with stress ratio (k) 2.

By comparing model with and without sill pillar, the effect of sill pillar in stabilizing stope and crown pillar in high horizontal stress area can be explained. The comparison is given in Figure 4.9. From the stress flow or the stress trajectories, it can be seen that in situ stress from side of the stope without sill pillar will be diverted into roof of the uppermost stope or floor of the bottommost stope. Before the stope is excavated, all the stress flows are in horizontal direction due to the stress ratio within the model is 2. After the stope is excavated until the third slice, all the stresses flow at the same level with the stope and filling material is diverted, indicated by the line is deflected into the roof or the floor as can be seen in Figure 4.9(a). This means that there is tendency the stress will be concentrated at roof and floor thus the amount will be higher.

When sill pillar is applied, accumulation of induced stress will be reduced due to there is gap between the opened stope and the filled stope. By providing this gap, sill pillar will give the same effect with the effect explained in the model with GSI 37.5 in Section 4.2.1. In addition, sill pillar gives another effect which is reducing diverted horizontal stress in roof and floor of the stope. In situ stress which flows in horizontal direction and located at the same level with sill pillar will relatively flow through the sill pillar and not diverted to the roof or floor of the stope as shown in Figure 4.9(b). Therefore, the stress concentration at both roof and floor of the last stope will be lower making better stope stability condition.

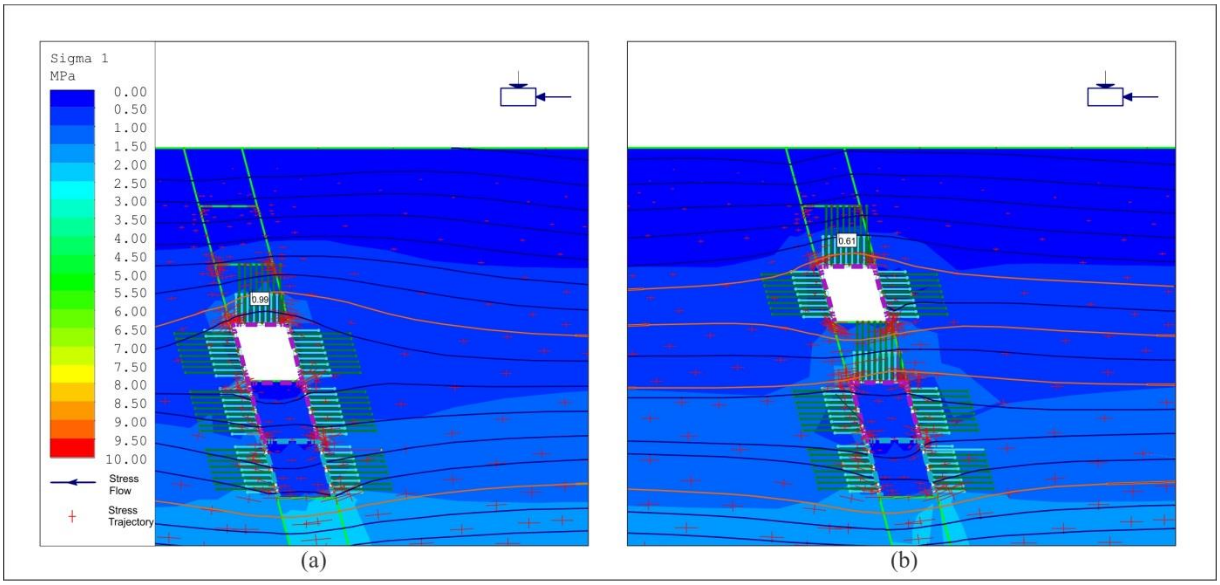

Figure 4.9. Effect of sill pillar on stress distribution around stope and crown pillar for a model with stress ratio 2.

The results of simulation for sill pillar application at different stress ratio show that sill pillar is effective for stabilizing stope both at high vertical stress and high horizontal stress condition. When rock support can no longer stabilize the uppermost stope at crown pillar area in overhand cut and fill, it is worthwhile to try leaving a portion of vein rock mass as sill pillar and mine the slice above it. The sill pillar application will reduce the maximum stress due to accumulation of induced stress thus increase the stope stability.

4.3. Sill Pillar Optimization

Previous analysis shows the effectiveness of sill pillar application to maximize crown pillar recovery. However, sill pillar is also formed by vein rock mass. Even though it can maximize crown pillar recovery, some portion of ore needs to be left behind as a sill pillar. It will be more beneficial if the sill pillar itself can also be optimized by minimize its thickness or even by completely extract it.

4.3.1. Optimization of Sill Pillar to Stope Thickness Ratio

In previous simulations, sill pillar to stope thickness ratio is set to be one. With this ratio, sill pillar has the same thickness with the stope thickness or height. To optimize sill pillar, it is worthwhile to try simulating smaller ratio which represents smaller sill pillar thickness. Figure 4.10 summarize simulation results for model with stress ratio 2 where the sill pillar ratio is 0.5 (Figure 4.10(a)) and 0.75 (Figure 4.10(b)). If the sill pillar thickness is half of the stope thickness, it can be seen that the sill pillar is fully yielded as shown in Figure 4.10(a). As sill pillar thickness in this model is reduced, the accumulation of induced stress from the stope below sill pillar on sill pillar rock mass and roof of the uppermost stope will be higher. Moreover, more horizontal stress at sill pillar level will be diverted into the roof of the uppermost stope. Therefore, stope floor which is formed by sill pillar rock mass will be heaving or heavily damage and the roof of the uppermost stope will be unstable. Thus it can be suggested that the ratio 0.5 is not suitable for the mine with the stress ratio 2.

If the ratio is increased into 0.75 as in Figure 4.10(b), both the sill pillar and stope roof is in better condition. The roof is stable while sill pillar stability improves. However, the sill pillar is still yielded thus monitoring in the field needs to be carried out during the excavation. If it is found that the floor is heaving or damage then remedial action needs to be taken for example by installing concrete at the floor. This result suggests there is possibility to use ratio 0.75 to minimize sill pillar thickness.

Optimizing sill pillar with the scenario shown in Figure 4.10(b) will left 11.25 m crown pilar thickness. If the previous stope height (5 m height) is used to mine the next slice, there will be no additional ore obtained from sill pillar optimization. Therefore, the next slice is excavated with stope height of 6.25 m and the result is given in Figure 4.10(c). It can be seen that crown pillar is in stable condition after excavation of stope with height 6.25 m. Additional 1.25 m thickness ore is obtained from the sill pillar optimization.

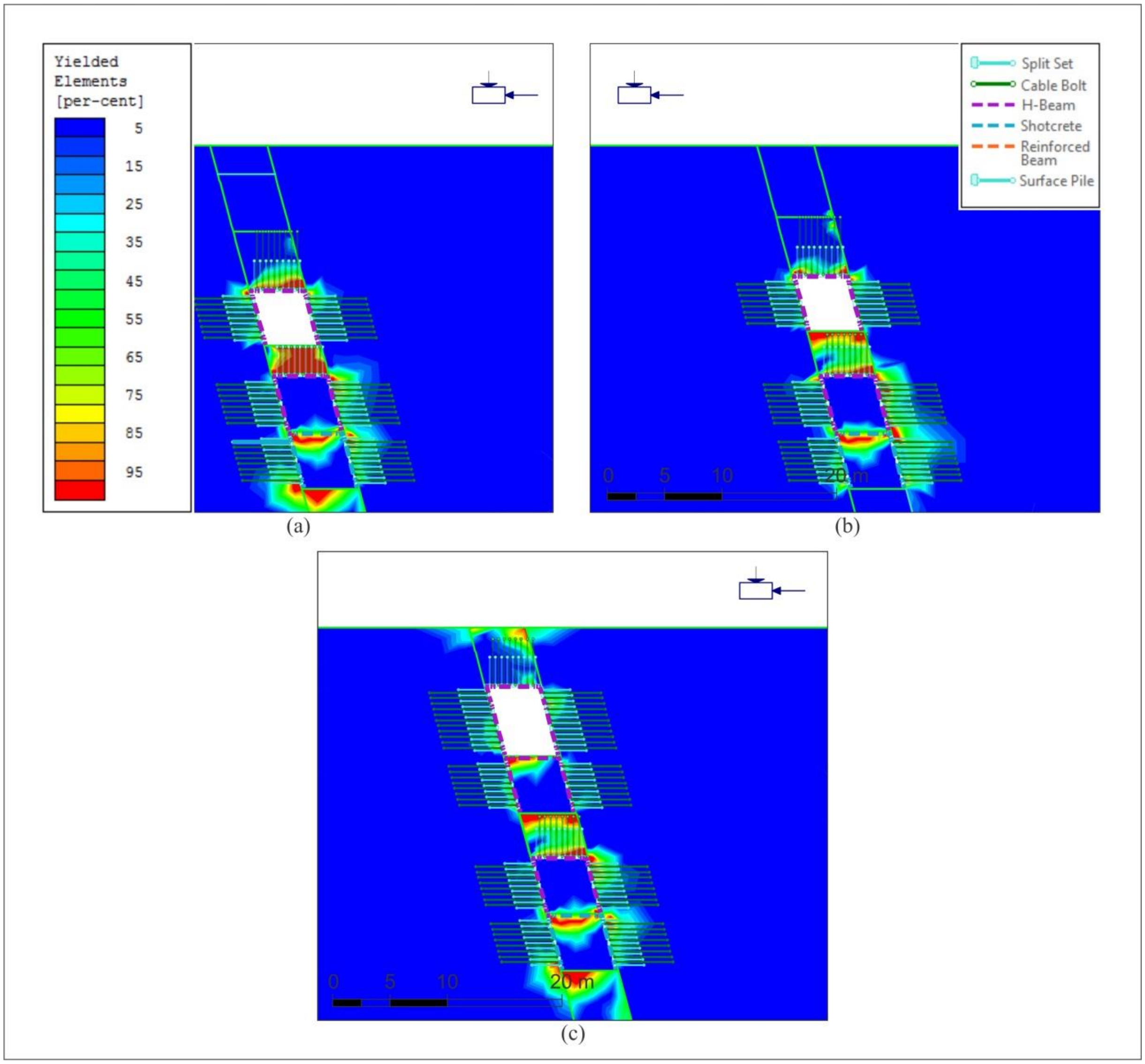

Figure 4.10. Stope and sill pillar stability in model with stress ratio 2 for different sill pillar to stope thickness ratio.

Sill pillar optimization for model with stress ratio 0.5 is given in Figure 4.11. Decreasing sill pillar thickness in this model will increase the accumulation of induced stress at the roof of the uppermost stope and crown pillar. As consequences, crown pillar in both sill pillar optimization models shown in Figure 4.11(a) and 4.11(b) are in unstable condition. The sill pillar stability also decreased by more yielded zone occurs at sill pillar. This result suggests optimization of sill pillar from sill pillar to stope ratio 1 to a lower ratio cannot be carried out for this model.

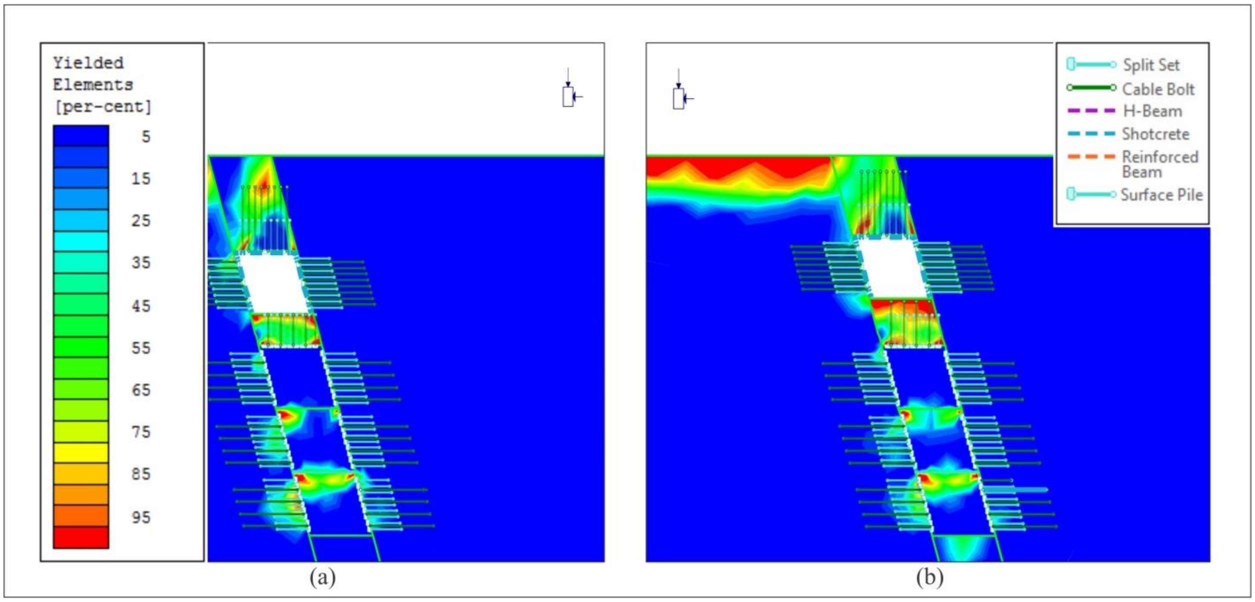

Figure 4.11. Stope and sill pillar stability in model with stress ratio 0.5 for different sill pillar to stope thickness ratio.

As already explained in Section 4.2.1, sill pillar in the model with GSI 37.5 has an effect of reducing the accumulation of induced stress at the roof of uppermost stope and crown pillar area. Reducing sill pillar thickness will increase the accumulation of induced stress both at sill pillar and roof of the uppermost stope. It can be expected that the same condition with the one in Figure 4.11 will occur where the crown pillar is in unstable condition. However, the effect of vertical stress is not high for this model since the stress ratio is 1. Therefore, accumulation of induced stress will be dominantly come from induced stress of the first three stopes and only few come from in-situ stress. As the result, the crown pillar is in stable condition as can be seen in Figures 4.12(a) and 4.12(b). Nevertheless, the floor needs to be monitored since the result shows the sill pillar is yielding.

Results in Figures 4.12(a) and 4.12(b) show the possibility to reduce the sill pillar thickness for model with GSI 37.5. However, further analysis by increasing height of stope above sill pillar to 7.5 m and 6.25 m as can be seen in Figures 4.12(c) and 4.12(d), respectively, indicates crown pillar failure occurs. Models in Figures 4.12(c) and 4.12(d) left 5 m thickness of crown pillar, the same thickness with model in Figure 4.3. From the result shown in Figure 4.3, it can be seen that 5 m crown pillar thickness is stable but the yield area at crown pillar is quite severe. As the stope height in models shown in Figure 4.12(c) and 4.12(d) is higher than in Figure 4.3, the induced stress from the stope opening becomes higher. As consequence, the crown pillar yields more than in Figure 4.3. This result shows that even though it is possible to optimize the sill pillar, it is not always possible to optimize the crown pillar as well. Simulation for sill pillar optimization needs to be followed by simulation for crown pillar optimization. If it is found that sill pillar thickness can be minimized while the crown pillar thickness cannot be minimized, it is better to use thicker sill pillar thickness in order to prevent possibility of failure at the stope floor.

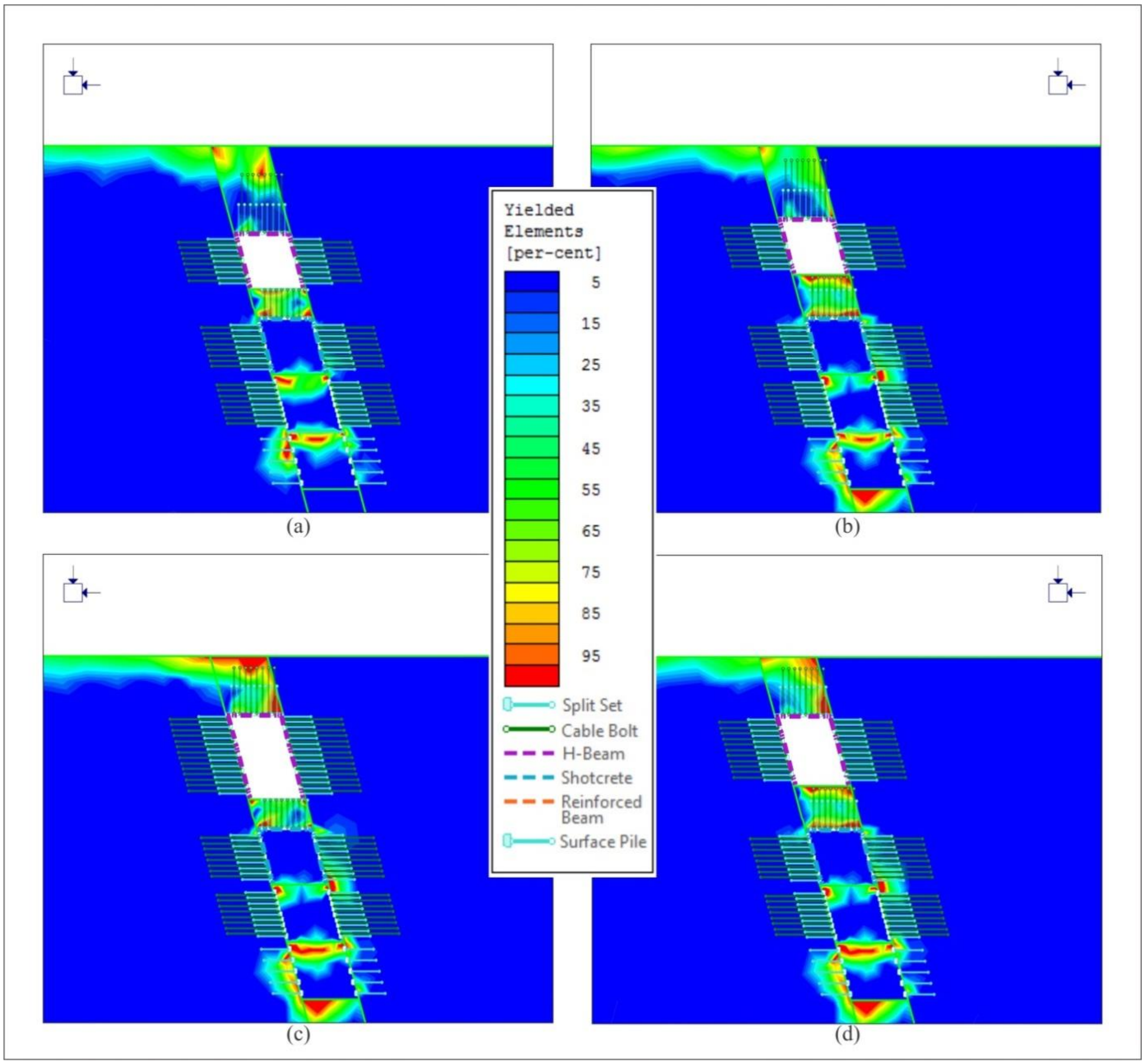

Figure 4.12. Stope and sill pillar stability in model with GSI 37.5 for different sill pillar to stope thickness ratio.

4.3.2. Sill Pillar Extraction

Another way to optimize sill pillar is by extracting sill pillar itself. Extracting sill pillar can be carried out by applying stronger filling material such as cemented hydraulic fill applied at underhand variant. To test the possibility to extract sill pillar, simulation is carried out at model with stress ratio 2 with the schematic shown in Figure 4.13. In Section 4.2.2, sill pillar is installed at the third slice to maximize crown pillar recovery at model with stress ratio 2 and stoping is continued at the fourth slice as shown in Figures 4.13(a) and 4.13(b). To extract the sill pillar, cemented hydraulic fill is inserted to the fourth slice after it is mined out. The sill pillar located at the third slice is then excavated under the cemented hydraulic fill as can be seen in Figure 4.13(c). In Figure 4.13(d), stoping is continued at the fifth slice to minimize crown pillar thickness into 5 m after the sill pillar is excavated.

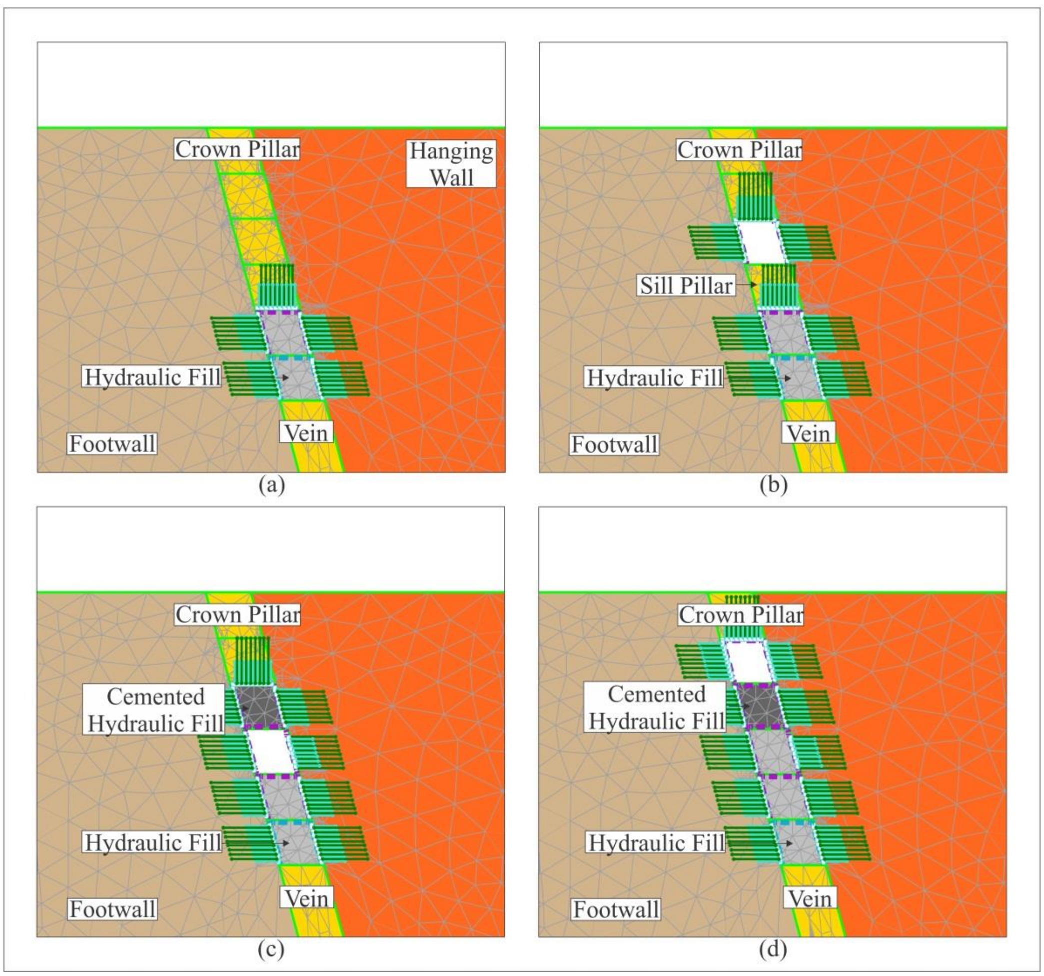

Figure 4.13. Schematic of sill pillar extraction for model with stress ratio 2.

The stability of stope and crown pillar during sill pillar extraction is given in Figure 4.14. From Figure 4.14(a), it can be seen that sill pillar extraction is in stable condition even without active type rock support in the roof. Yielded zone forming an arch shape is occurs above the stope which is filled by cemented hydraulic fill. However, it is not fail since it is supported by the cemented hydraulic fill mass. After the sill pillar is completely mined out and filled, stoping is continued at the fifth slice and it can be seen in Figure 4.14(b) that both stope and crown pillar is in stable condition. This result shows that there is possibility to extract sill pillar after the stope above sill pillar is filled by using cemented hydraulic fill.

One thing that needs to be considered when applying this technique to extract sill pillar is the cost of cemented hydraulic fill. As already discussed in the second chapter, the cost of cemented hydraulic fill is relatively higher than hydraulic fill. This cost along with the other mining cost need to be evaluated against the revenue from the sill pillar extraction. If the sill pillar has a high grade then the possibility to apply such technique will be higher.

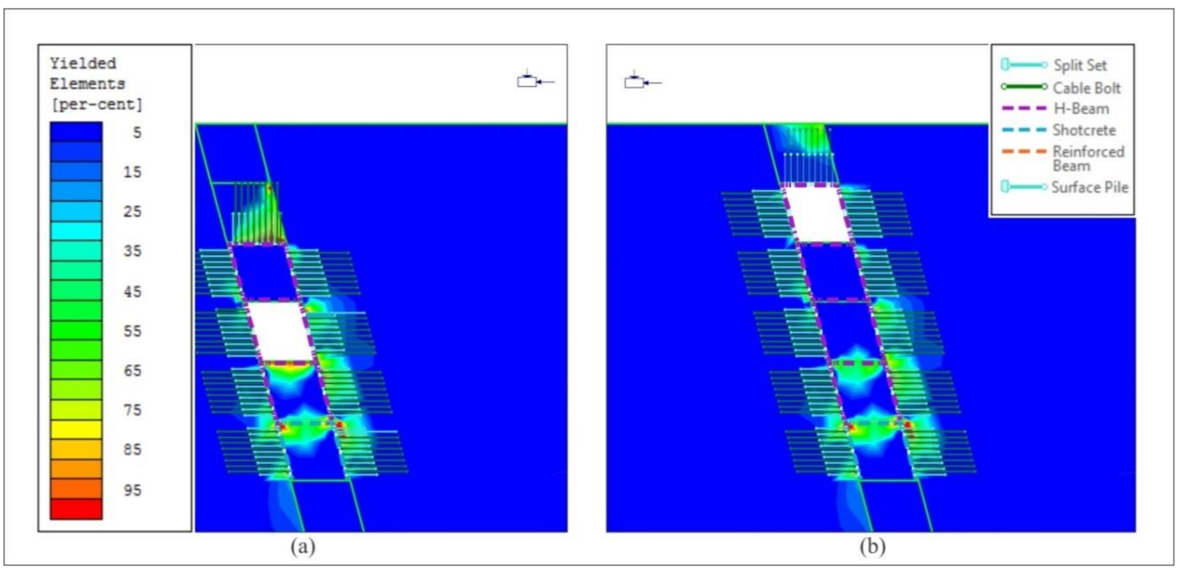

Figure 4.14. Stope and crown pillar stability during sill pillar extraction.

4.4. Conclusion

Sill pillar application is very effective to stabilize stope as well as to maximize crown pillar recovery. One of its effective utilization is in maximizing crown pillar recovery of model with stress ratio 2 where it can minimize a 20 m thickness of crown pillar into 5 m by leaving a 5 m thickness of sill pillar at 15-20 m in depth. In general, the main effect of sill pillar application is reducing accumulation of induced stress at the stope above it and the crown pillar. There is possibility to optimize the sill pillar as well by reducing the sill pillar to stope thickness ratio. However, sill pillar rock mass may be yielded and there is possibility that the floor of the stope above it will be damaged. Monitoring during excavation of stope above sill pillar needs to be carried out and if it is found that the floor is heaving or damage then remedial action needs to be taken for example by installing concrete at the floor. It is also possible to extract sill pillar by applying stronger filling material such as cemented hydraulic fill at the mined out stope above the sill pillar. After the fill is completely cured, the sill pillar can be extracted. However, the cost of fill needs to be considered when applying such technique. Therefore, this technique is possible to be applied when the ore grade is relatively high.

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Chapter 5

Application of Surface Grouting for Stope Stabilization at Shallow Depth

The application of sill pillar has provided an alternative countermeasure method for stope instability in crown pillar area. Not only improves the stope stability, its application can also maximize crown pillar recovery by allowing additional slice to be mined at crown pillar area. One of its advantage is it can be applied without any cost since applying sill pillar only needs to left portion of ore rock mass as a pillar. Therefore, it is very suitable for overhand cut and fill mine where the ore grade is not so high. However, sill pillar application in mine with high grade ore will result in some portion of high grade ore left behind as a pillar.

When the ore grade is high, there will be opportunity to apply more expensive countermeasure method with the potential to extract more ore than the one sill pillar did. From the analysis in the last two chapters, the key of the crown pillar optimization in overhand cut and fill is stabilizing stope at shallow depth. As the stope progressing upward, the stope will be located in more shallow depth. Since the stope is located at shallow depth, there is possibility to apply countermeasure method for stope instability from the surface.

Application of surface grouting for stope stabilization at shallow depth will be discussed in this chapter. Grouting material will be injected from the surface to strengthen the crown pillar rock mass above the uppermost stope. Having stronger rock mass strength than before grouted, it is expected that stope stability will improve so that crown pillar recovery will be increased. However, its application which is injecting grouting material from the surface will have an impact on the protected forest environment. Therefore, not only its effectiveness but also the way to maximize its effect with the minimum possible distraction to the protected forest environment needs to be studied. The application of surface grout will be studied by means of numerical model. The result will be discussed in detail in the following sections.

5.1. Rock Mass Strength of Grouted Material for Numerical Model

The effect of grouting material to the rock mass strength will depend on physical properties of the rock mass. Rock mass with intensive joint will have stronger rock mass strength when being grouted since grouting material will filled the joint. Some joint will be eliminated making improvement on rock mass strength. Additional effect will be given if the intact rock of rock mass is porous. Not only filling the joint within the rock mass, grouting material will also infiltrate into the voids within the rock with high porosity. This will lead to improvement of intact rock mechanical properties. The last effect that will increase rock mass strength if the chemical grout injected to the rock mass is reduction of water flowing through the joint in the rock mass. Water flowing through the joint will reduce the overall rock mass strength thus reducing the water flow will increase the strength. Nevertheless, the effect will be different for a different type of rock.

In Indonesian gold mine, vein bearing-Au deposit is formed by quartz rock as can be seen in Figure 5.1. This type of rock has very small porosity and void. There is a little possibility that grouting material can infiltrate the voids within the quartz. Thus it will not increase mechanical properties of the intact rock. Chemical grouting will not considered to be used as grouting material for stope stabilization due to its cost. Therefore, the improvement due to reduction of water flowing within the rock mass will not be considered in this study. Improvement of quartz rock mass by grouting material is mainly caused by infiltration of grouting material to the joint within vein rock mass. By filling the joint within the rock mass, the RQD of the rock mass will increase. This will lead to increasing rock mass strength of the vein as a whole.

Barton et al. (2002) assumes fine, cementicious grouting may cause moderate, individual effect on RQD around 30-50% due to elimination of some joints. This percentage of RQD improvement will be used as basis for rock mass strength improvement due to application of surface grouting. From the new RQD value, the new GSI value will be determined by using GSI chart as shown in Figure 5.2 (Hoek et al., 2013). Finally, complete rock mass strength can be obtained by using the new GSI value as an input in Hoek and Brown Failure Criterion

(Hoek and Wood 1987; Hoek and Brown 1988; Hoek 1990; Hoek et al. 2000; Hoek and Diederichs 2006).

Figure 5.1. Quartz bearing-Au rock.

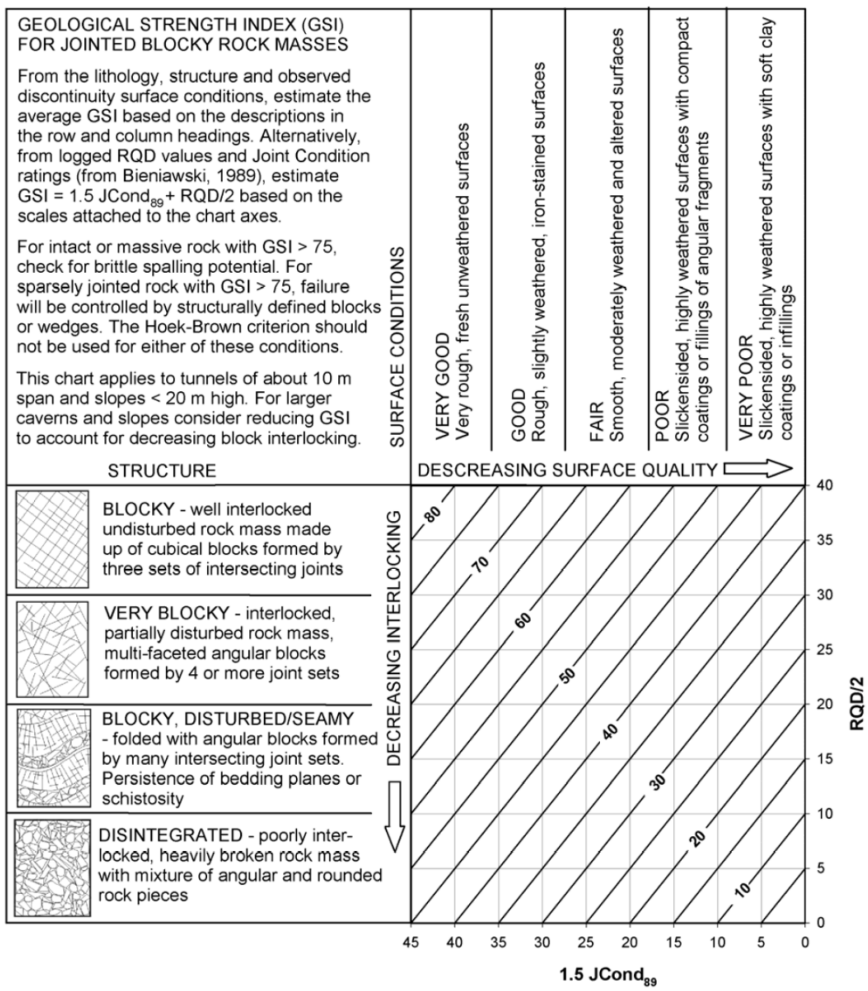

Figure 5.2. Quantification of GSI by Joint Condition and RQD (After Hoek et al. 2013).

5.2. Numerical Simulation of Surface Grouting Application for Stope Stabilization at Shallow Depth

Since the aim of numerical simulation in this chapter is not only to understand the effectiveness of surface grouting application in stabilizing stope at shallow depth but also possibility to minimize its impact at surface area, three dimensional numerical analysis is carried out by using finite difference method. Software named FLAC3D is utilized to simulate three dimensional models. By using three dimensional analysis, the area of protected forest that needs to be grouted to stabilize stope at shallow depth can be identified. This area is the impacted area due to application of surface grout at protected forest. To maintain the environment of protected forest, it is important to minimize this area as small as possible. The simulations cannot be carried out by using two dimensional numerical analysis because the grouted area in out-of-plane direction cannot be determined since two dimensional analysis assumes that the geometry in out-of-plane direction is same with in plane direction.

For the simulation, a 100 m cube with 5 m width vein dipping in 75^o as shown in Figure 5.3 is constructed. The same 5 m height stope with the stope as in the basic model for two dimensional analysis is then constructed from the bottom into the upper part of the vein. This stope will be excavated later starting from the bottom and progressing upward to simulate the overhand cut and fill mining method. The material characteristics are set to comply with the Mohr-Coulomb Failure Criterion. The boundary conditions for the model are defined as follows; displacements in the western and eastern of the model as well as in northern and southern of the model are only permitted in the y and z directions as well as in the x and z directions. At the lower limit of the model the displacement is only permitted in the direction of x-direction and y-direction. The stress ratio (k) is set to be one.

Rock mass properties that will be used for this simulation is the one for model with GSI 37.5 (Table 5.1) since based on analysis using two dimensional numerical model, crown pillar optimization is needed. It will be investigated whether application of surface grouting can minimize the crown pillar thickness as sill pillar did. In addition, the impacted area of protected forest due to surface grouting application will also be evaluated.

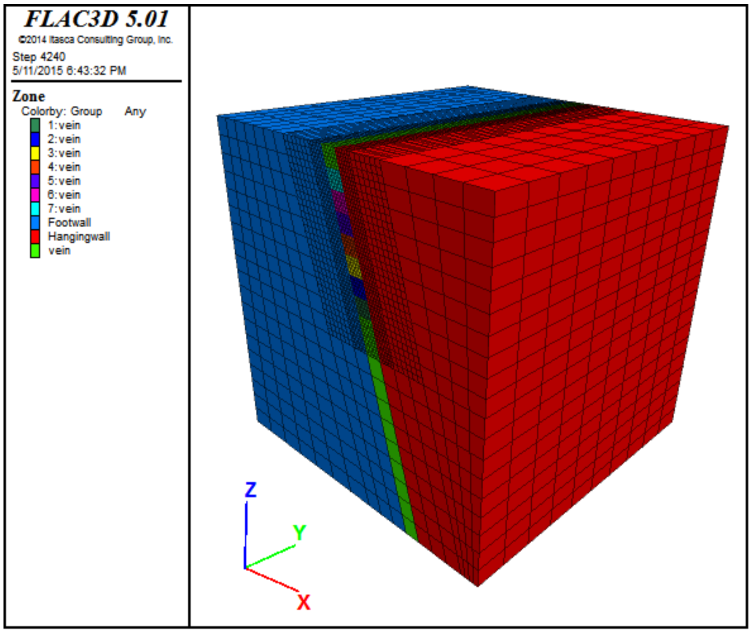

Figure. 5.3. Numerical model for simulation of grouting material.

Table 5.1 Rock mass properties for simulation of surface grouting application.

Geological Strength Index (GSI)	Zone	Hoek Brown Parameter				Mohr-Coulomb Parameter				
		σ_{ci} (MPa)	m_b	s	a	C (MPa)	ϕ	σ_t (MPa)	E_{rm} (MPa)	v
37.5	Hanging wall	2	2.68	0.00096	0.51	0.12	33.55	-0.00072	107.6	0.3
	Foot wall	5	2.68	0.00096	0.51	0.16	40.73	-0.0018	269	0.3
	Quartz Vein	29	2.68	0.00096	0.51	0.30	53.76	-0.01	1560.3	0.2

Notes: σ_{ci} = uniaxial compressive strength of intact rock material; m_b, s, a = material constant for Hoek-Brown Failure Criterion; C = rock mass cohesive strength; ϕ = rock mass friction angle; σ_t = uniaxial tensile strength of rock mass; E_{rm} = Young's modulus of rock mass; v = Poisson's Ratio.

5.2.1. Simulation of Model without Application of Surface Grouting

This simulation is carried out to obtain the minimum crown pillar thickness from three dimensional analysis with the rock support utilization as countermeasure for stope instability. The result will be compared later with the minimum crown pillar thickness with surface grouting application. The properties of rock support are the same with the properties given in second chapter. The results of simulation are given in Figure 5.4. The figure shows cross section view of crown pillar taken at the center of model perpendicular to the vein strike. The color indicates plasticity state of each zone. The zones in which the stresses satisfy the yield criterion are indicated with the color shown in the legend. The plot also indicates the zone which is at active failure (indicates with -n) or has failed in the past (indicates with -p) at the end of simulation. By looking at the whole pattern of this plasticity indicator, the failure or stable condition of stope and crown pillar can be determined.

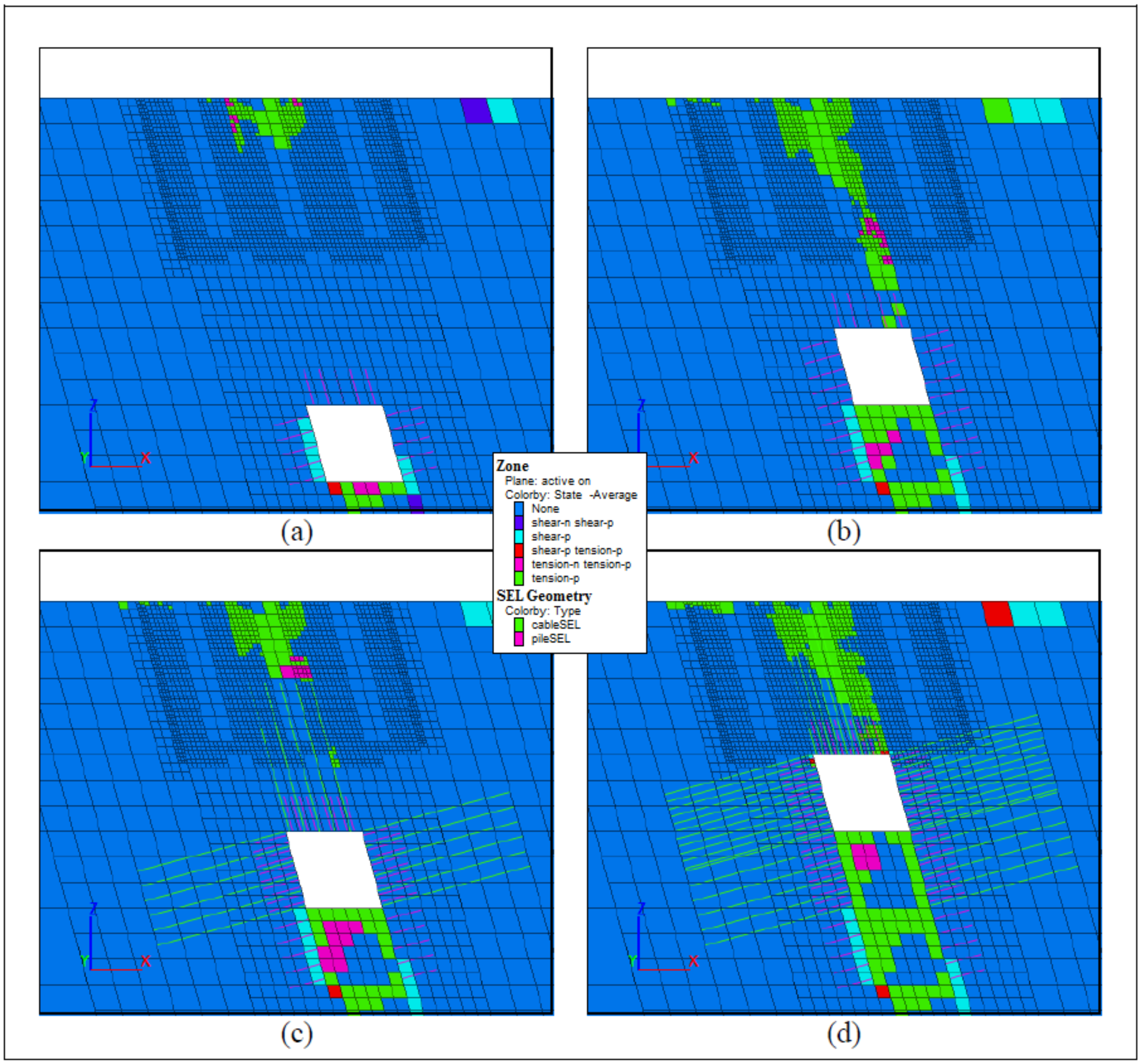

Figure. 5.4. Simulation result of model without application of surface grouting.

Based on the simulation results, the stope at the first slice is in stable condition after supported by split set with 1 m x 1 m spacing as can be seen in Figure 5.4(a). Crown pillar rock mass near the surface starts to yield due to induced stress from the opening. As the stoping continued to the second slice by using the same rock support design, stope is still in stable condition (Figure 5.4(b)). However, the crown pillar rock mass is heavily yielded. If stoping is continued at the upper slice, the probability of stope and crown pillar failure will be higher. To improve crown pillar stability, cable bolt with 1 m x 1 m spacing is added in second slice and the yielded zone is reduced significantly as shown in Figure 5.4(c). However, when the third slice is excavated even by tighter cable bolt spacing which is 0.5 m x 0.5 m, the development of yield area in crown pillar rock mass cannot be prevented. If the fourth slice is excavated, the crown pillar rock mass which is already yielded will collapse to the stope opening. Stope at the third slice is in stable condition since the yielded zone did not form sinkhole pattern. Therefore, minimum crown pillar thickness for this model is 10 m. The result is slightly better compared with the analysis in two dimensional where 15 m crown pillar thickness need to be spared. Two dimensional analysis is carried out with the plane strain assumption that made the result more pessimistic.

5.2.2. Simulation of Model with Application of Surface Grouting

Previous analysis with rock support shows crown pillar in model with GSI 37.5 is heavily yielded making stope cannot progress further. To improve crown pillar stability, surface grouting is applied with the injection of cement grout. Since previous analysis shows that the yield area occurs at vein area at about 10 m depth, injection will be carried out to vein rock mass with 10 m depth. Radius of grouting from the center of borehole is designed to be 2.5 m with the borehole located at the center of vein to cover all of the vein area. The numerical model for this design is shown in Figure 5.5. Figure 5.5(a) shows the three dimensional model while Figure 5.5.(b) shows cross section taken at the center of model perpendicular to vein strike. The surface grouting will be applied on the vein area only since the previous analysis shows the yielded zone occurs at the vein. The yielded zone at the hanging wall and footwall side will not be grouted since it did not cause failure and also to minimize the impact of grouting at the surface environment. If it is found from the analysis that improvement needs to be made on the hanging wall or foot wall side then the grouting can be applied on those area.

Strength properties of grouted rock mass in the model are calculated based on the RQD improvement as explained in previous section. The model simulates rock mass with GSI 37.5. Based on chart in Figure 5.2, the value of y and x axis is 18.75 if it is assumed that both parameters give an equal effect in determining GSI value. The GSI of the grouted rock mass will improve into 47 with the following calculations:

- RQD/2 = 18.75
- RQD (before grouted) = 2 x 18.75 = 37.5
- RQD improvement due to surface grout = RQD x 50% = 18.75
- RQD (after grouted) = 37.5 + 18.75 = 56.25
- GSI = 1.5 $JCond_{89}$ + RQD/2 = 18.75 + 28.125 = 46.875 ≈ 47 (1)

The RQD improvement is based on assumption explained in Section 5.1. The grouted rock mass GSI which is 47 can be obtained by plotting the value of new RQD/2 to the value of 1.5 $JCond_{89}$ or simply by using the Equation (1). One should use the RQD improvement carefully so that the RQD value after grouting will not exceed the maximum RQD value which is 100%. Based on the new GSI, the complete grouted rock mass strength can be obtained by using Hoek and Brown Failure Criterion and the summary is given in Table 5.2.

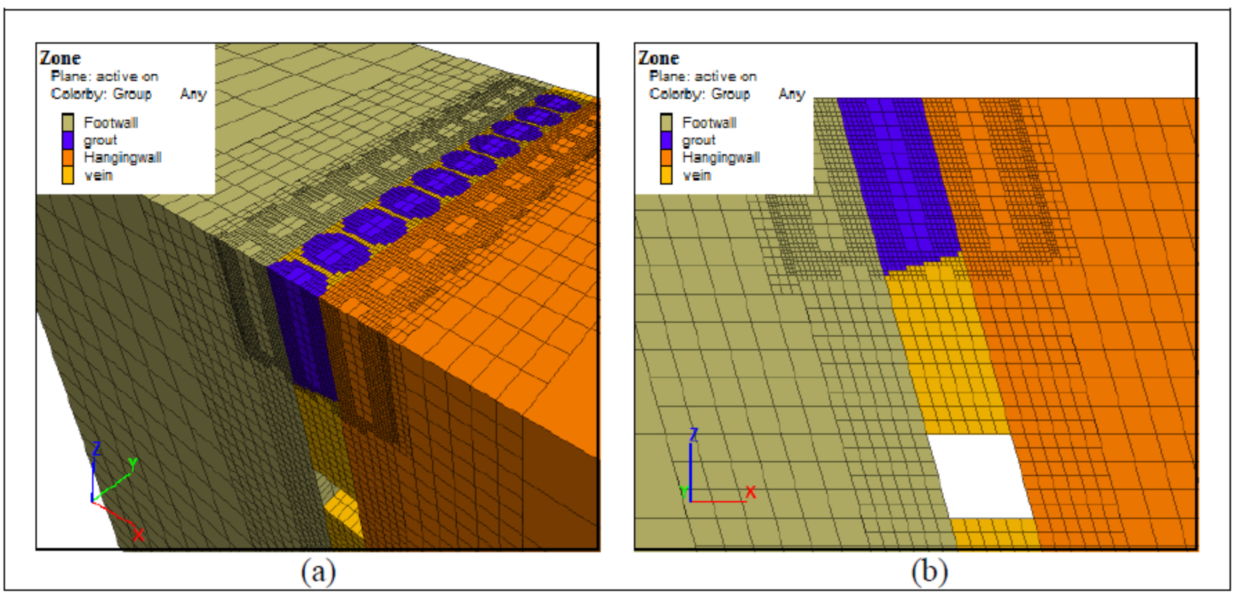

Figure. 5.5. Numerical model for simulation of surface grouting application.

Table 5.2 Cement Grouted Rock Mass Properties

Geological Strength Index (GSI)	Zone	Hoek Brown Parameter				Mohr-Coulomb Parameter				
		σ_{ci} (MPa)	m_b	s	a	C (MPa)	ϕ	σ_t (MPa)	E_{rm} (MPa)	v
47	Hanging wall	2	3.76	0.0027	0.50	0.14	36.31	-0.00147	203.78	0.3
	Foot wall	5	3.76	0.0027	0.50	0.19	43.56	-0.0036	509.45	0.3
	Quartz Vein	29	3.76	0.0027	0.50	0.37	56.28	-0.021	2954.82	0.2

Notes: σ_{ci} = uniaxial compressive strength of intact rock material; m_b, s, a = material constant for Hoek-Brown Failure Criterion; C = rock mass cohesive strength; ϕ = rock mass friction angle; σ_t = uniaxial tensile strength of rock mass; E_{rm} = Young's modulus of rock mass; v = Poisson's Ratio.

Simulation results of model with application of surface grouting are given in Figure 5.6. From the comparison between simulation results in Figures 5.6(a) and 5.4(a), the yield zone at crown pillar area is reduced significantly after surface grout is applied. Higher rock mass properties make it more difficult for crown pillar rock mass to yield. The simulation is continued to the second slice with the same rock support design as used by model in Figure 5.4(c). The result as can be seen in Figure 5.6(b) shows that stope is in stable condition. When the third slice is excavated as shown in Figure 5.6(c), yielded zone above the stope occurs. However, it is not forming an arch shape so that it can be considered that stope in the third slice is in stable condition. Optimization of crown pillar from the model with rock support is achieved as the stope in the fourth slice is in stable condition with the application of surface grouting as can be seen in Figure 5.6(d). Yield zone occurs especially at the corner of stope roof but the pattern did not suggest any failure occurs. Therefore, it can be said that the application of surface grouting to stabilize stope at shallow depth is effective. The crown pillar thickness is minimized from 10 m thickness in model without surface grouting application into 5 m thickness in the one with surface grouting application.

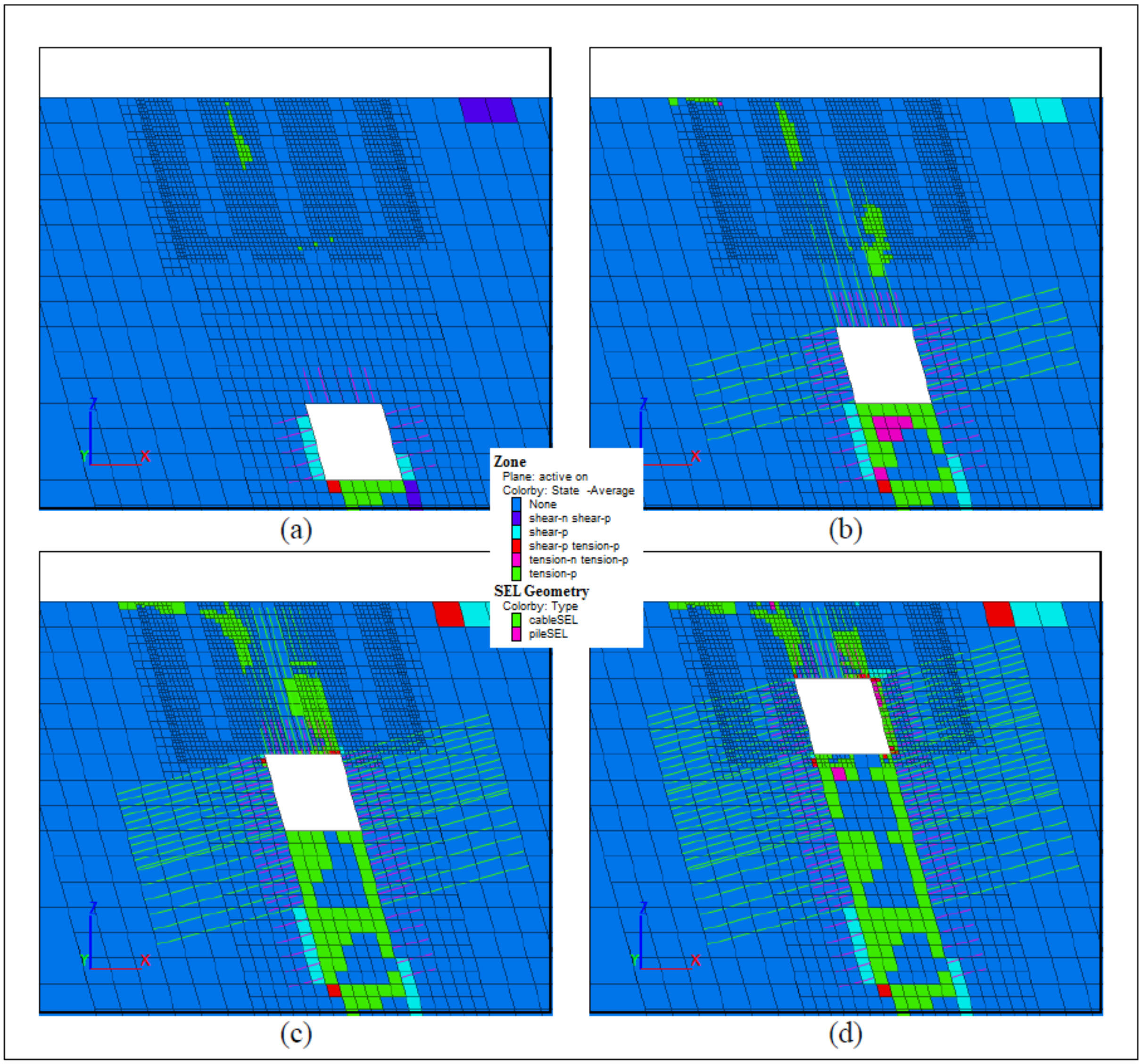

Figure. 5.6. Simulation result of model with application of surface grouting.

5.3. Reduction of Surface Grouting Area

Application of surface grouting has been proven effective to stabilize stope at shallow depth as well as to maximize crown pillar recovery in the previous section. Nevertheless, from environmental point of view, it will give an impact to the protected forest environment such as the need to clear the land for cement grout rig and distraction to soil fertility. Therefore, the impact needs to be minimalized by reducing the grouted area. In this section, several scenarios to reduce the grouted area will be analyzed. It will be evaluated whether it is possible to reduce the grouted area while keep maintaining stability of the stope at shallow depth and also crown pillar.

The first scenario is carried out simply by add spacing between column grout from the previous simulation. Figure 5.7(a) shows plane section at the surface of model for this simulation. By adding spacing, the impacted area at the surface of protected forest will be reduced. This simulation also aims to see whether the injection of column grout will have an effect to the surrounding rock which is not grouted at a certain radius. If the column grout injection also improves the yield zone of ungrouted area, then it can be concluded that there is an effect at a certain radius from the column grout.

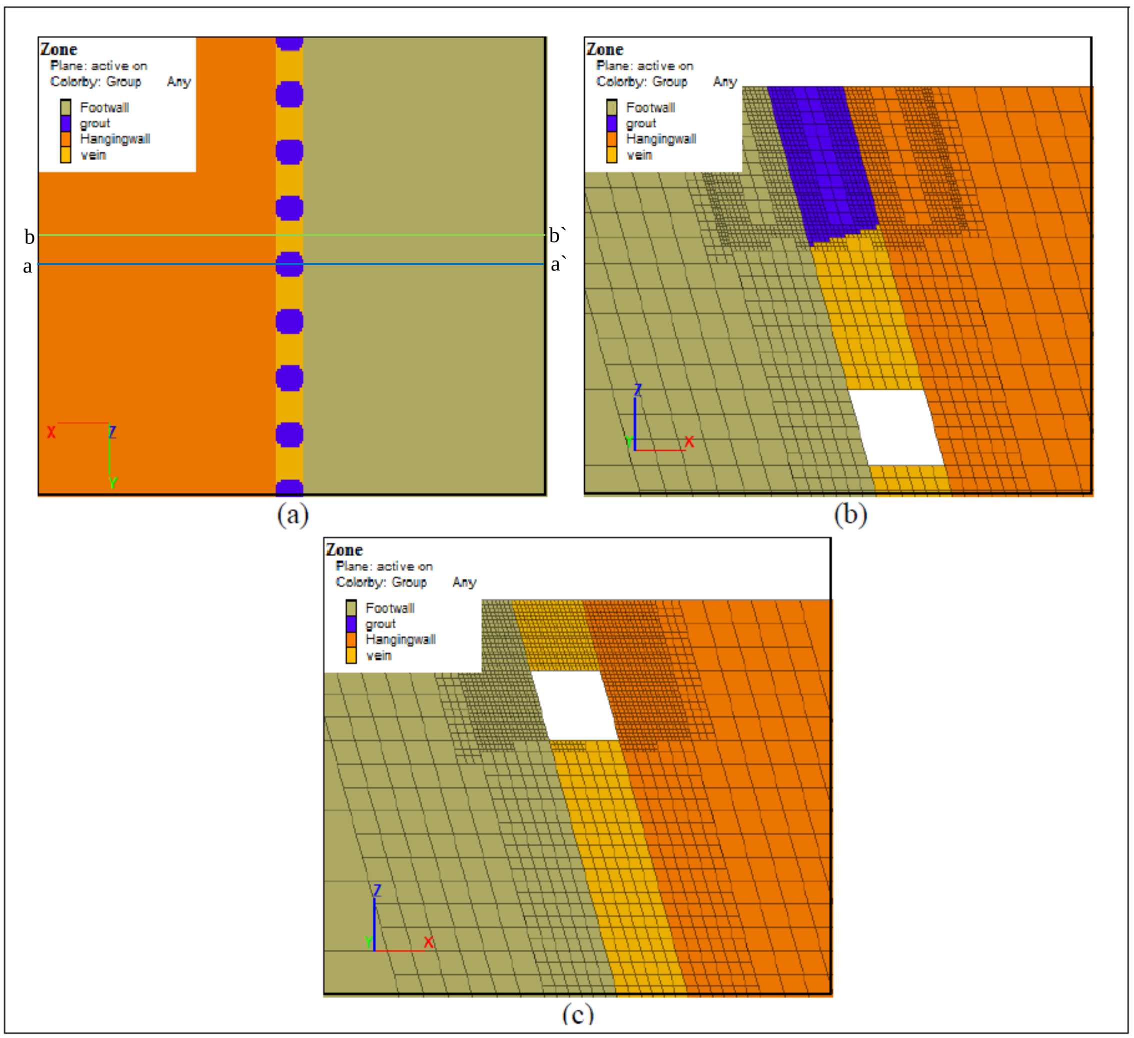

Figure. 5.7. Numerical model for simulation of surface grouting application with spacing 5 m.

Two cross sections, which are a-a` and b-b`, were taken to evaluate the result. The cross section a-a` where the vein is grouted is shown in Figure 5.7(b) while b-b` where the vein is ungrouted is shown in Figure 5.7(c). The simulation results are summarized in Figure 5.8.

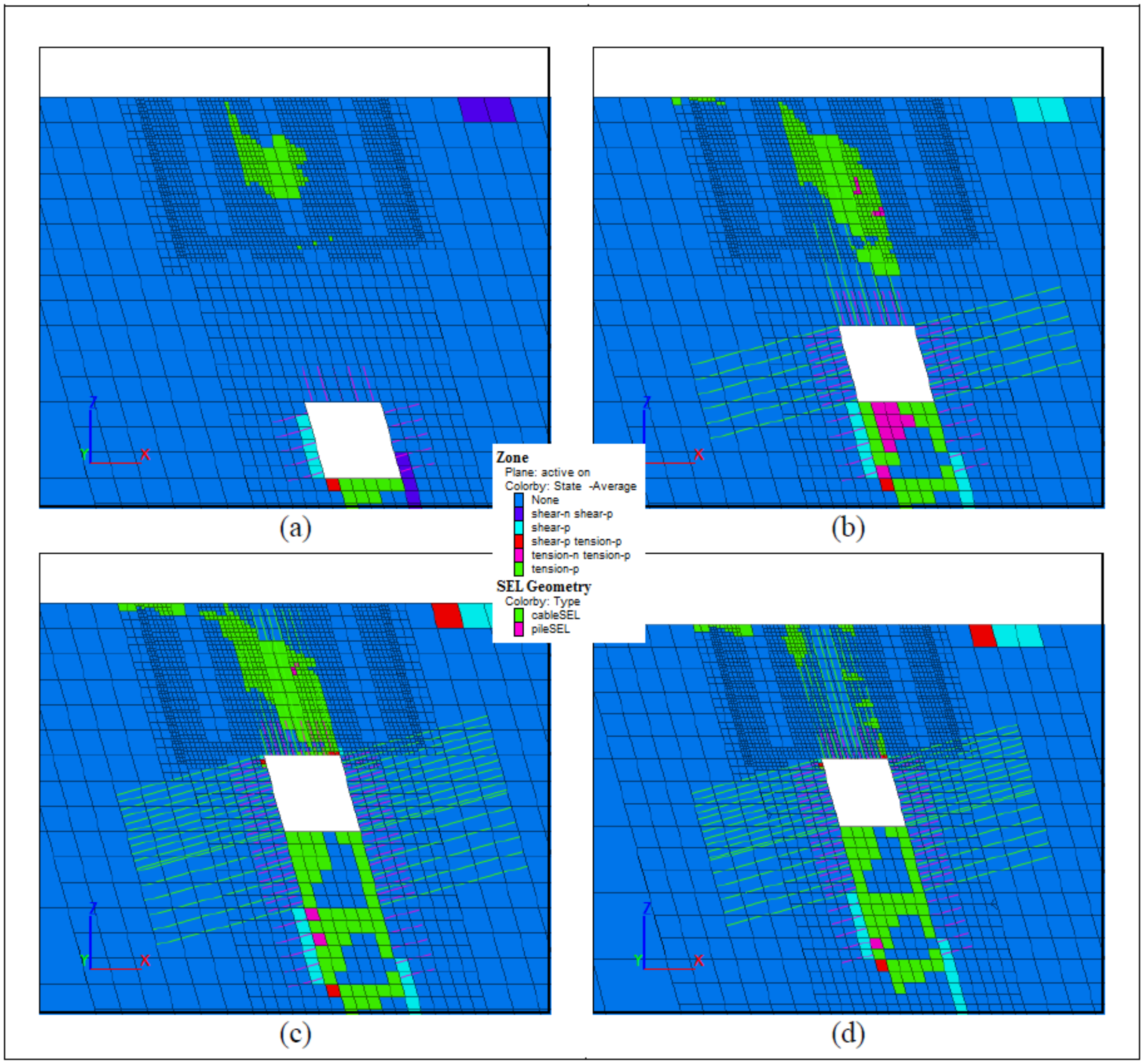

Fig. 5.8. Simulation result of model with application of 5 m spacing surface grouting.

Figures 5.8(a)-5.8(c) show the simulation results for first until third slice excavation in section a-a`. It can be seen that the yield zone at the crown pillar does not improve much when it is compared with the result in Figure 5.4 where the column grout is not applied at the model. However, from the yield zone pattern, it can be considered that the first until third slices are in stable condition since no yield zone forms stable arch pattern. Meanwhile at the b-b` section as shown in Figure 5.8(d) the improvement at the third slice is obvious. The yield zone is reduced much from the one in Figure 5.4(d).

Similar trend occurs at the excavation of fourth slice as given in Figure 5.9. The crown pillar in the section a-a`, as shown in Figure 5.9(a), is yielded more than the one in section b-b` as shown in Figure 5.9(b). The stress will be concentrated at the grouted rock mass since it has higher rock mass properties than the surrounding rock. This condition has caused grouted rock mass to yield more than the surrounding rock. The stress of surrounding rock mass will be reduced hence the yield area reduced. Such condition did not occur when the column grout is tightly spaced such as in the previous simulation shown in Figure 5.6. The concentrated stress will be divided evenly among the grouted rock so that the grouted rock mass is not yielded as much as when the spacing is applied. Nevertheless, this result shows there is possibility to give some spacing in the column grout application to reduce the impacted area at the surface since the result of first until third slice show the stope and crown pillar is in stable condition. The fourth slice is also possible to be extracted by applying tight monitoring program during the excavation especially at the grouted area. If it is found that progressive displacement occurs, standing support such as H-beam needs to be installed to support the area.

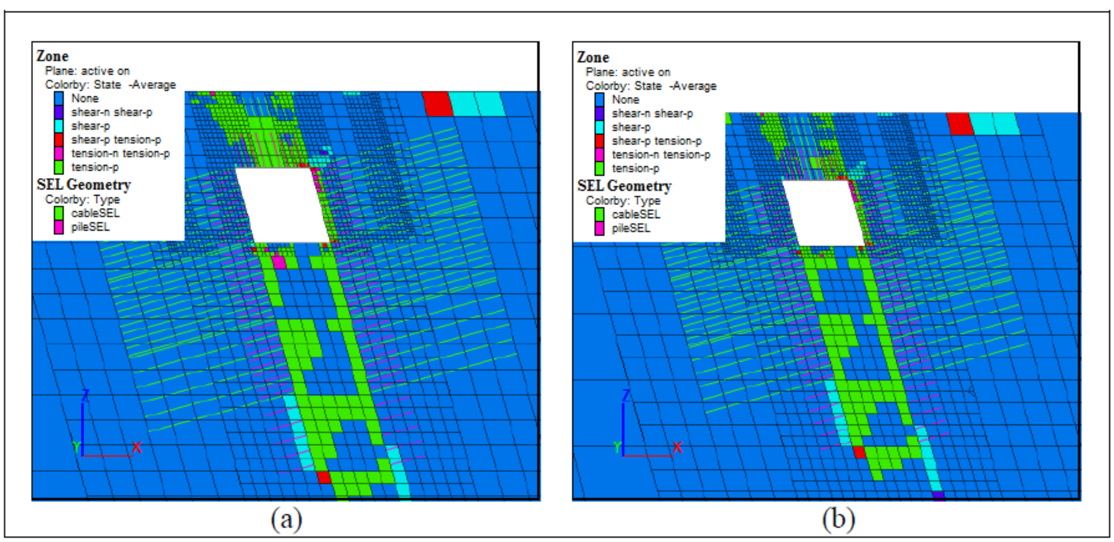

Figure. 5.9. Simulation result of model with application of 5 m spacing surface grouting for the fourth slice.

The simulation results of 5 m spacing column grout show that surface grout has an effect to the surrounding rock mass. Based on this result, if the yield zone covers a large area, it is worthwhile to try grouting at the center of the yield zone to have an obvious effect with minimum impact at environment rather than grouting the entire yield zone. To prove this statement, another simulation by using smaller radius of column grout which is 1.25 m is carried out. Plane section at the surface of model for this simulation is shown in Figure 5.10(a). Two sections to evaluate the model at grouted and ungrouted area is taken in section a-a` and b-b`, respectively. The cross section a-a` is given in Figure 5.10(b) while the cross section b-b` is given in Figure 5.10(c).

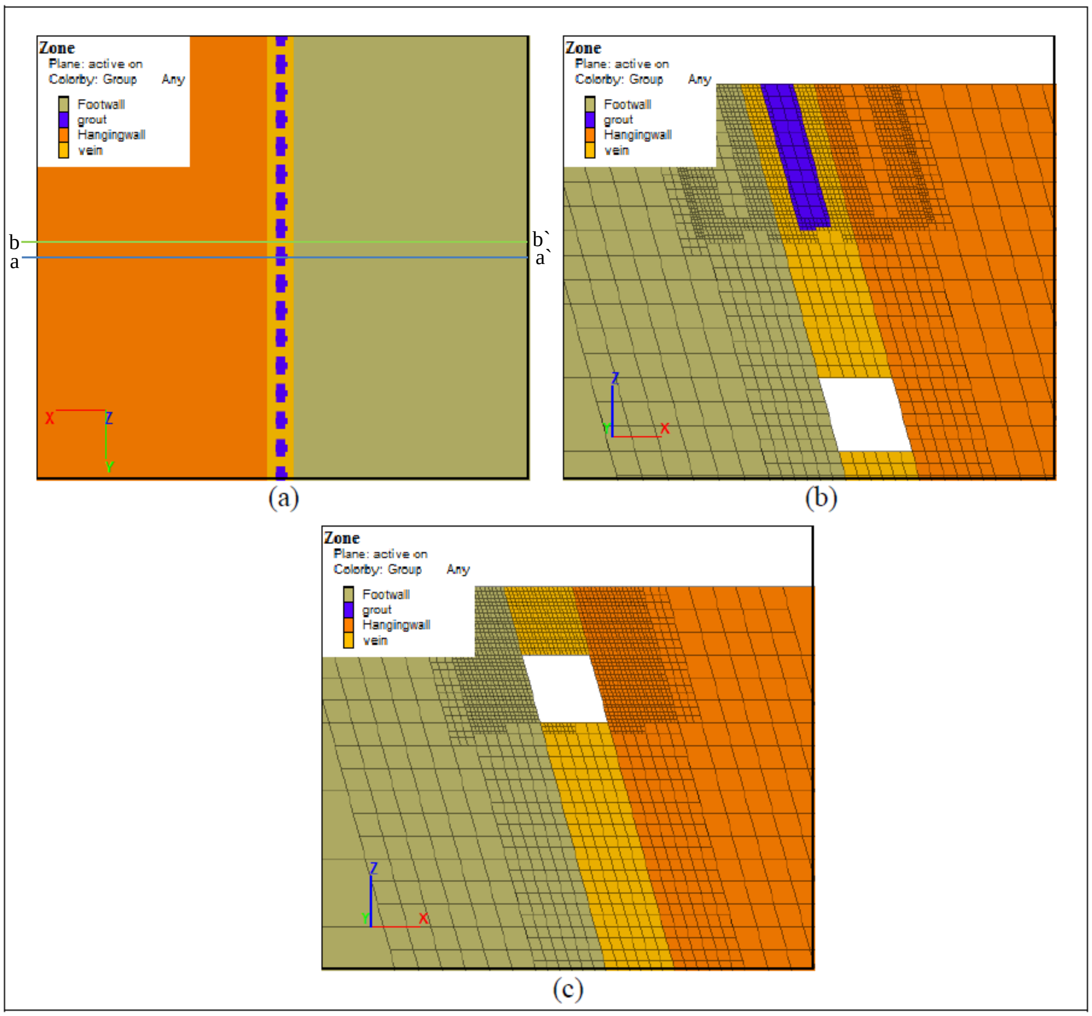

Figure. 5.10. Numerical model for simulation of surface grouting application with radius 1.25 m.

The simulation results of model with 1.25 m radius surface grout are summarized in Figure 5.11. The results for the first three slices in section a-a` are given in Figures 5.11(a)-5.11(c). Having higher rock mass properties and slender geometry than the surrounding rock, the grouted rock mass yields in tensile state when the stope in the first slice is excavated in Figure 5.11(a). The stope is in stable condition. The yielded zone extends as the stope progressing upward in Figure 5.11(b). Stope instability does not occur up until this stage. The yield zone extends further as the stope in third slice is opened. Looking closer to the yielded zone, the extension of yield zone occurs at two third of the grouted rock mass in the upper side. The yield area at the bottom side of grouted is not extend. Therefore, stope can be considered as stable. Moreover, if the section is moved to section b-b` as can be seen in Figure 5.11(d), the crown pillar rock mass is only slightly yielded. It is even in better than the condition in Figure 5.6(c) where the entire vein is grouted.

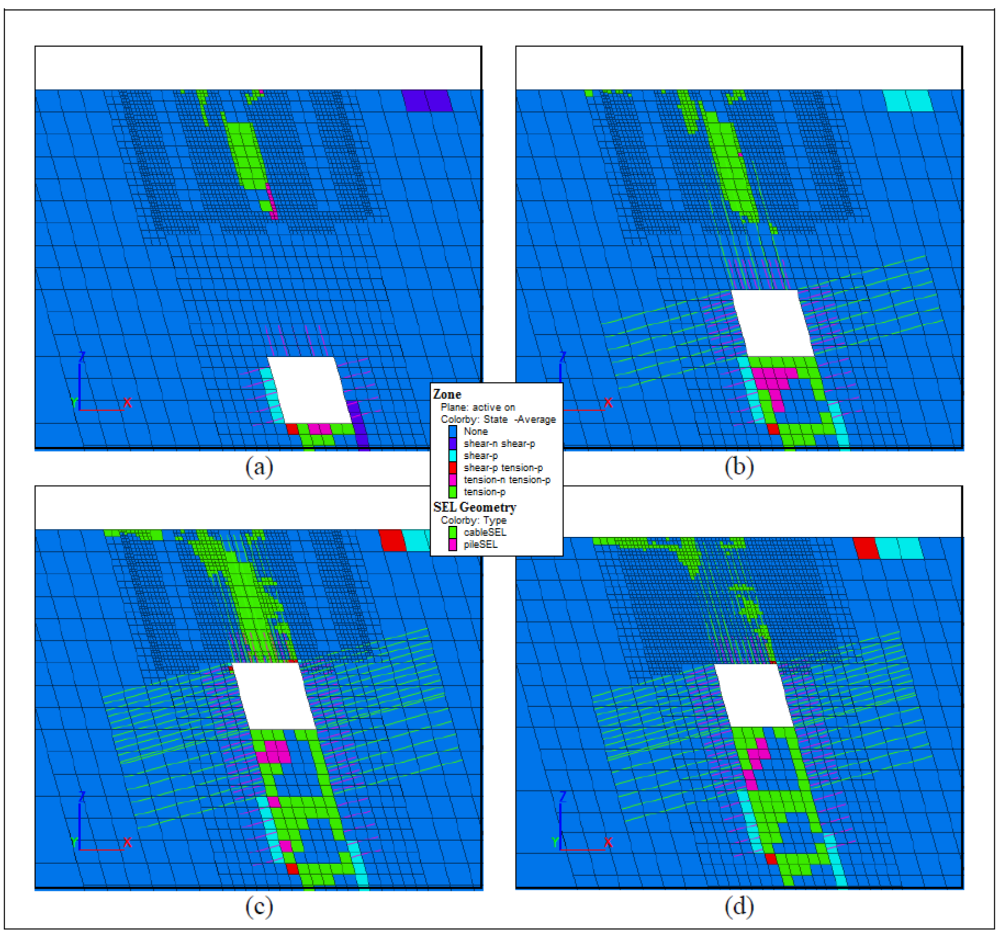

Figure. 5.11. Simulation result of model with application of 1.25 m radius surface grouting.

When the last slice is excavated, there is possibility that the grouted vein at crown pillar will fail as can be seen in Figure 5.12(a) for crown pillar stability in section a-a'. There is possibility that the yield zone, developed during the stoping from the first slice until the third slice, fails into the fourth slice when the stope is excavated. However, the section b-b` shown in Figure 5.12(b) is in stable condition. The improvement is obvious if it is compared to the model without application of surface grout. Therefore, it can be said that there is effect of grouted area to its surrounding rock. The stability condition shown in Figure 5.12(a) is the result of active type rock support and surface grout application. Passive type support is not installed in the model. In order to ensure safety during the excavation of fourth slice, passive type rock support such as H-beam can be installed especially at the area below the surface grout. Monitoring is also needed to be installed to monitor the deformation at roof during the excavation.

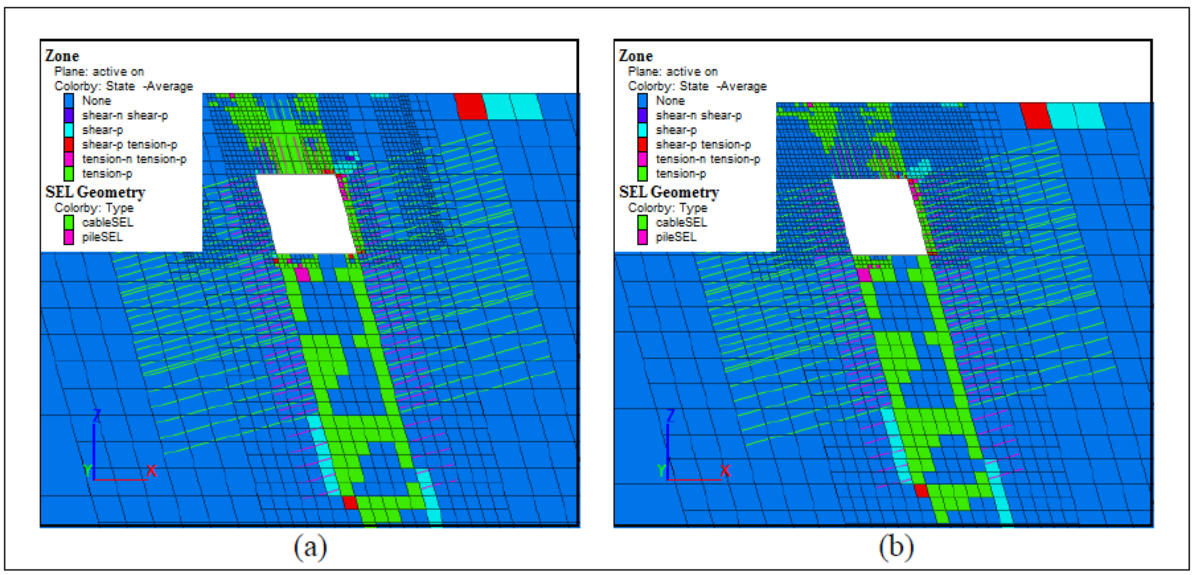

Figure. 5.12. Simulation result of model with application of 1.25 m radius surface grouting for the fourth slice.

Besides showing the possibility to reduce the grouted area in stabilizing stope at shallow depth, simulation results of 5 m spacing and 1.25 m radius surface grout also show that grouting has an effect to the ungrouted rock mass surrounding the grouted one. In ungrouted model simulation, the yield zone is continuous along the vein strike. When grouting with 5 m spacing or 1.25 m radius is applied, yield zone of rock in the territory of ungrouted rock is reduced. As guidelines for reducing the column grout impact at the surface, if the yield zone covers a large area, the best practice is to try grouting at the center of the yielded zone to have maximum effect rather than grouting the entire yielded zone.

Figure 5.13 shows contour of maximum principal stress taken at plane section which cut the grouted vein. This contour can explain the reason behind improvement made by surface grouting. All of contour is taken when the first slice is excavated at the model. Figure 5.13(a) is the contour of maximum principal stress of ungrouted model. When the model is ungrouted, most of the vein is in compressive state which indicates with negative value of maximum principal stress. As the vein is grouted in Figure 5.13(b), it can be seen that the contour of both hanging wall and foot wall slightly become blue while the grouted vein itself becomes red. This indicates the grouted area is having more tensile condition while its surrounding hanging wall and foot wall become less tensile.

Clearer result can be seen in Figures 5.13(c) and 5.13(d). In Figure 5.13(c) where there are parts of vein which are grouted and ungrouted, the ungrouted area becomes more compressive or less tensile, indicates with blue color. This has caused the ungrouted area not having tensile failure as shown in the Figure 5.8(d) while the grouted area is having tensile as indicates in Figure 5.8(c). In simulation where the column grout radius is reduced into 1.25 m, it can be seen clearly from Figure 5.13(d) that the surrounding rock becomes more compressive that indicates by blue color. This simulation results indicate that the application of surface grout will not only affect the grouted area but also the rock mass surrounding the grouted area.

From this case study, guidelines for applying surface grouting at protected forest can be obtained. First of all, simulation of stope supported by rock support needs to be carried out in order to locate portion of rock mass that potentially to fail and also the depth of yield area. The surface grout in form of column grout can then be applied at that portion of rock mass to strengthen its rock mass strength thus prevent it from failure. Since the previous analysis shows that it will also affect the rock mass surrounding the grouted area, surface grout should be applied at the center of yield area. Furthermore, spacing can be given in order to minimize the grouted area in the surface.

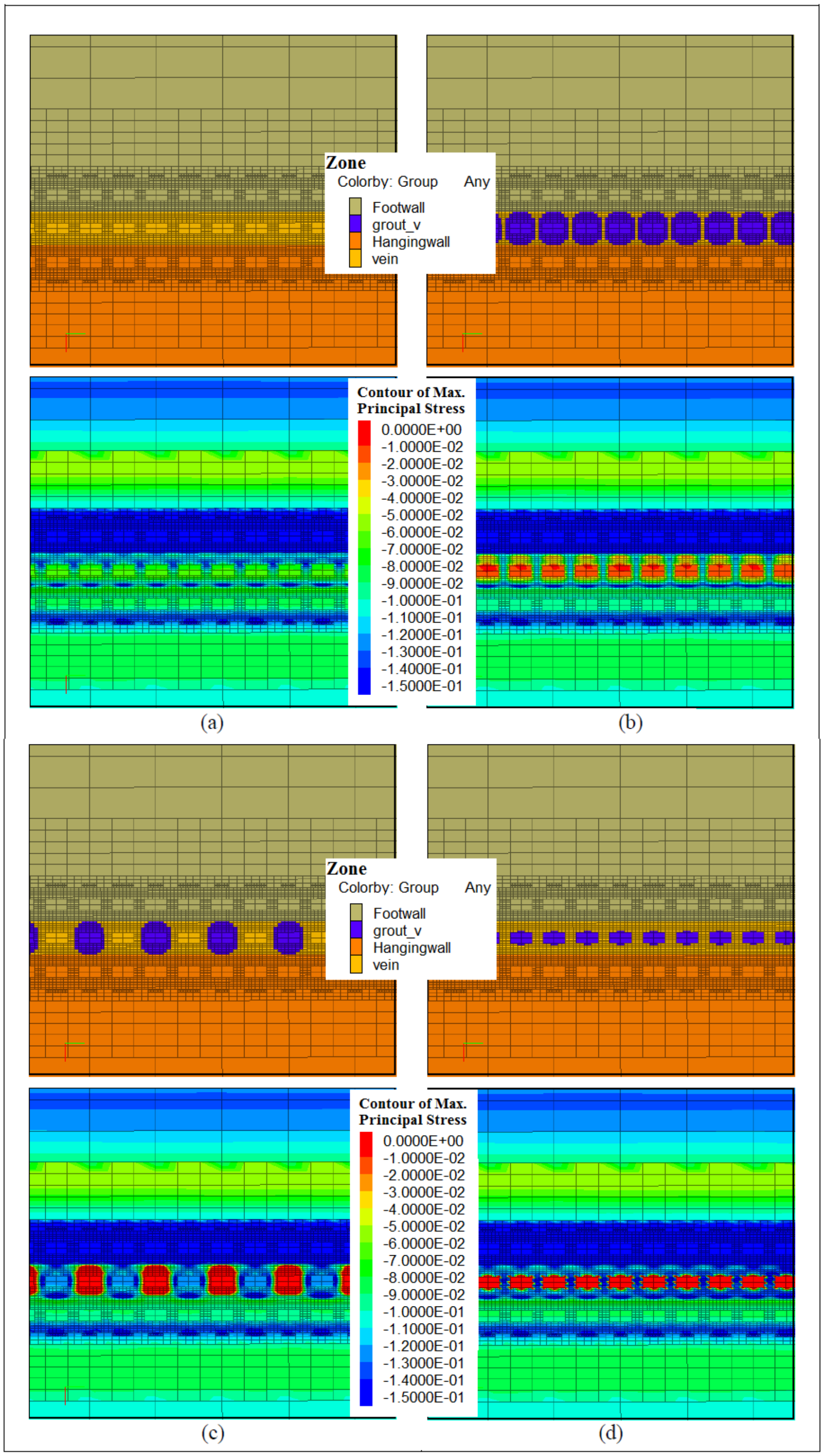

Figure. 5.13. Contour of maximum principal stress for different scenario of surface grout application.

Since the surface grouting effect in stabilizing stope and crown pillar is by strengthening the rock mass strength, it can be applied at wide range of conditions. At a low vein dip condition, failure may develop in hanging wall area as shown by results of simulation in Section 2.3. For such condition, surface grout can be injected at hanging wall area to strengthen the hanging wall rock mass with the same technique used in this chapter. Optimum radius and spacing need to be simulated to find the best design for given mine conditions. For wider vein width, yield zone may also cover both vein and hanging wall as can be seen in Figure 2.10 in Section 2.4 for model with vein width of 6.25 m. For yield pattern shown in that figure, it is suggested to apply surface grout at the center of yield area with vertical borehole so that the borehole will start from the hanging wall zone through the vein rock mass. More than one row of column grout may be needed depend on the given mine conditions. Yield area at model with various geological conditions and stress ratios tend to be developed at vein rock mass as can be seen in Sections 2.5 and 2.6. Therefore, it is better to use inclined borehole with the same inclination with the vein dip to inject the column grout and strengthen the vein rock mass. If it is found that the hanging wall area also has potential to fail then surface grouting can be applied at hanging wall area.

5.4. Guideline for Crown Pillar Optimization in Protected Forest

The result in the last two chapters has proved the applicability of surface grouting and sill pillar to maximize crown pillar recovery from the technical aspect. When the mine condition allows both countermeasures to be applied, not only the technical aspects but also economical aspects need to be considered to determine the best countermeasure to maximize crown pillar recovery. Moreover, as cut and fill is applied in protected forest, environmental aspects also need to be taken into the consideration.

From the economical point of view, the cost of surface grout is higher than sill pillar but it can give higher ore recovery. If the application of surface grout can generate net income based on economic analysis, crown pillar recovery optimization should be carried out by using surface grout. Another thing that should be noted when applying surface grout is it can only be applied if the government based on environmental impact analysis allows the mining company to installed grout at surface of protected forest. Therefore, two other things that need to be considered when applying surface grout are the ore grade and environmental impact analysis.

If the ore grade is high but it is not allowed to cause such impact to the protected forest environment then application of sill pillar with the sill pillar extraction can be an option. The cost will be higher than applying surface grout since it needs a large amount of cemented hydraulic fill compare with the amount of cement grout needs to be injected at the vein rock mass. When the cost of cemented hydraulic fill or surface grout is higher than the revenue generated from crown pillar recovery, the best option is to apply sill pillar with sill pillar to stope ratio optimization. The ore generated from crown pillar optimization with this method will not as much as from the one with surface grout or sill pillar extraction but still it can generate more ore than if it is only rock support is used for crown pillar optimization.

5.5. Conclusion

Application of surface grouting as an alternative countermeasure method for stope instability at shallow depth has been discussed in this chapter. Since ore vein bearing gold rock mass is formed by quartz which has small porosity, improvement by grouting material is mainly caused by infiltration of grout material to the joint within vein rock mass. This effect will improve the rock mass strength by improving the RQD value of the rock mass. From the results of numerical simulation, the injection of grouting material from the surface is proven effective to stabilize stope at shallow depth. Stope with 5 m thickness crown pillar is in stable condition by injection of surface grout at the center of vein along the vein strike with radius 2.5 m. It improves crown pillar recovery from previous analysis with the rock support as countermeasure method where 10 m thickness crown pillar needs to be spared.

Application of surface grout is more beneficial than sill pillar since it can give higher recovery. However, it can only be applied if the ore grade is quite high and it is allowed by the government through environmental impact analysis to installed grout at surface of protected forest. Simulation with reduction of surface grout area is carried out to see the possibility to minimize its impact at surface of protected forest. The results show that there is possibility to reduce the grout area by using 5 m spacing or 1.25 m radius while keep having the same minimum crown pillar thickness. If the yield zone covers a large area, it is worthwhile to try grouting at the center of the yielded zone to have an obvious effect rather than grouting the entire yielded zone.

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Chapter 6
Conclusions

From the results discussed in previous chapters, the following conclusions were obtained:

6.1. Perspective for Cut and Fill Mining Method Application in Protected Forest

With the increasing environmental and social issues in the natural resources development, the application of underground mining method can become solution to maximize the benefit of natural resources development as well as to minimize the environment and social impacts. Underground mining method can be applied under protected forest where conflict often arises between the needs to promote economic development through natural resources development and to preserve environmental condition. Indonesia, as one of the country with the large area of protected forest and mineralization found under protected forest, has permitted underground mining operation under protected forest with a strict regulation. One of its strict regulations is prohibition of subsidence to occur at the surface of protected forest.

Several underground mining methods cannot be applied under protected forest. Having conduct mining by caving the ore body and country rock, caving method is not suitable to be applied in protected forest. The unsupported method can be applied at some extent but its long term stability of the opening after mine closure is one of major concerns on its application at protected forest. Following the disadvantages of the two other methods, the supported method is the most suitable method to be applied in protected forest.

Cut and fill underground mining, the most widely applied supported method among the others, offers long term protection from subsidence with its backfilling application. Two variants of cut and fill which are underhand and overhand are widely practiced including in Indonesia. The underhand cut and fill is commonly used in weak rock mass condition. In this variant, first slice is executed from the upper level progressing downward. Backfill material is inserted after the slice fully mined out. The next slice will be executed under the backfill material. The backfilling material should be strong enough to stabilize country rock as well as protecting mining operation activity at the lower level. As consequences, high initial and operating cost occur to provide strong backfilling material such as cemented hydraulic fill. Overhand cut and fill variant, where stoping is started from bottom level and progresses upward, offers lower cost since it can applied various type of filling materials such as waste rock, pneumatic fill and hydraulic fill. Having this cost advantages, overhand variant is preferable to underhand variant when the rock mass condition is not weak.

Having backfilling in the operation has given cut and fill subsidence protection advantage over the other method. However, there are records of several surface subsidence cases due to application of this method in the past. Subsidence as reported by several researchers has occurred due to failure of stope at shallow depth during the excavation. When stope at shallow depth collapse, failure may continue until the rock mass that separates uppermost stope with the surface which named crown pillar. Increasing crown pillar thickness could be a way to prevent surface subsidence. However, part of crown pillar in cut and fill mining method which is directly above the stope is formed by ore body. Increasing its thickness will increase the stability, yet reduce mining recovery since higher volumes of ore body are left behind as a pillar. Therefore, maintaining stope stability during extraction is the key to prevent subsidence in cut and fill application.

6.2. Effect of Stoping in Cut and Fill Mining Method under Different Mine Condition

To prevent stope failure, it is important to understand stress distribution around stope and crown pillar area. As stope progresses upward in overhand cut and fill or downward in underhand cut and fill, differential stress at crown pillar increases due to accumulation of induced stress from stope opening. Crown pillar in underhand variant is yielded as the stope progresses downward but it remains stable since the fill below crown pillar is supporting it. At the other hand, crown pillar in overhand cut and fill is more likely to fail as the stope progresses upward due to higher differential stress condition. For stope stability, stope in underhand variant is more stable than the one in overhand variant due to application of cemented hydraulic fill. Both roof and wall of the stope in overhand cut and fill are more unstable than the ones in underhand. This result suggests that underhand cut and fill gives a better stability condition to the stope and crown pillar. More detailed investigation is needed to stabilize stope and crown pillar in overhand cut and fill.

Simulation of overhand cut and fill in different mine condition has been carried out. The first simulation is carried out for different vein dip where the results suggest crown pillar instability is more likely to occur in cut and fill mine with low vein dip. Special attention needs to be given on the hanging wall side since stress will be more concentrated at the hanging wall zone when stoping is carried out at vein with low dip. In various vein widths, differential stress at crown pillar in model with wider vein width will be higher due to higher induced stress from wider stope opening. For different geological condition, the model with lower geological condition will have higher differential stress at crown pillar area thus crown pillar and stope will fail easily. Different stress distribution will occur for mine with different stress ratio. The stress will be concentrated at roof and floor of the stope when stress ratio (k) around the stope is higher than one. On the contrary, stress will be concentrated around the wall of the stope when the stress ratio around the stope is lower than one. Moreover, the simulation of overhand with different filling material has concluded that properties of filling material have no effect to the stope and crown pillar stability.

Subsidence were found at the surface of several models where the failure reaches crown pillar area. If stable arch is formed after the stope is failed, it is almost certain that subsidence will not occur at surface based on simulation results. The certainty will be higher if the stope is in stable condition. Therefore, stope stability is the key to prevent subsidence. This result highlights the importance of rock support and other countermeasure methods to stabilize stope and crown pillar in various mine conditions which will be discussed in the next chapters.

6.3. Active and Passive Type Rock Support as Countermeasure for Stope Instability in Crown Pillar Area

The common countermeasure method for stope instability which is rock support is simulated for overhand cut and fill in various conditions. Two types of rock support which are active and passive type support are simulated to see its effectiveness on stabilizing stope and crown pillar area. From the simulation results of the model with different geological condition, it can be concluded that in more severe geological condition, more supporting capacity is needed to stabilize stope. Simulation results of model with GSI 25 show that strongest passive type rock support which is reinforced beam needs to be installed to stabilize stope from the first slice. As simulation is carried out for stronger rock mass, i.e. with GSI 37.5 and 50, active type rock support starts to have an effect in stabilizing stope while passive type is only needed to support stope in the crown pillar area for model with GSI 37.5. For a good rock mass condition with GSI above 50, only active type support system is needed to stabilize stope and crown pillar.

Based on result of simulations for model with different stress ratio, active type support system is not effective for supporting stopes in case the ratio of horizontal stress to vertical stress larger than 1 because the large failure zone is developed in the roof. Therefore, the passive type support should also be installed in the stopes in order to maintain the stability of stope and crown pillar if the stope is excavated at high horizontal stress conditions. The rest of simulations for active and passive type application as countermeasure method for stope in various vein dips and widths suggest that more supporting capacity is needed as the stope opened in lower vein dip and wider vein width. The direction of active type rock support in the wall side of stope has influence on crown pillar stability especially at hanging wall area.

6.4. Sill Pillar Application to Maximize Crown Pillar Recovery in Overhand Cut and Fill Underground Mine

The application of rock support has proven effective to support stope and also crown pillar in various mine conditions yet thick crown pillar still needs to be spared in several conditions.

An alternative countermeasure method by using pillar named sill pillar is introduced. Applying sill pillar can be carried out by abandon uppermost unstable slice from the simulation of stope supported by rock support as pillar and stoping is continued at level above the sill pillar. Based on simulation results, crown pillar recovery optimization is achieved by application of sill pillar. Sill pillar can minimize 15 m thickness crown pillar in model with GSI 37.5 and model with stress ratio 0.5 and 0.75 into 5 meter thickness. Moreover, it is proved very effective in model with high horizontal stress ratio where it can minimize a 20 m thickness of crown pillar into 5 m by leaving a 5 m thickness of sill pillar at 15-20 m in depth.

There is also possibility to optimize the sill pillar by reducing the sill pillar to a stope thickness ratio or extracting the whole sill pillar. The results suggest that there is possibility to optimize the sill pillar by reducing its sill pillar to stope thickness ratio from 1 into 0.75 or 0.5 for model with GSI 37.5 or model with stress ratio 2. However, sill pillar rock mass may be yielded and there is possibility that the floor of the stope above it will be damaged. Monitoring during execution of stope above sill pillar needs to be carried out and if it is found that the floor is heaving or damage then remedial action needs to be taken for example by installing concrete at the floor. Further simulations shown crown pillar thickness can be optimized after the sill pillar is optimized. Results of simulation also show that it is also possible to extract sill pillar by applying stronger filling material such as cemented hydraulic fill at the mined out stope above the sill pillar. After the fill is completely cured, the sill pillar can be completely extracted. One of the concerns when applying such technique is the cost of the filling material. Therefore, this technique is possible to be applied when the ore grade is relatively high.

6.5. Application of Surface Grouting for Stope Stabilization at Shallow Depth

When the ore grade is quite high and it is allowed by the government through environmental impact assessment to apply countermeasure from the surface, surface grout can be applied to stabilize stope at shallow depth. Grouting material can be injected from the surface in form of column grout to strengthen the crown pillar rock mass above the uppermost stope. Improvement of rock mass strength by application of surface grout is calculated based on

RQD improvement since the effect of grouting material to vein rock mass mainly caused by infiltration of grouting material to the joint within the rock mass. From the new RQD value, the new GSI value will be determined by using quantification of GSI chart. Finally, complete rock mass properties can be obtained by using the new GSI value as an input in Hoek and Brown Failure Criterion.

From the result of numerical simulation, the injection of grouting material from the surface is proven effective to stabilize stope at shallow depth. Stope with 5 meter thickness crown pillar is in stable condition by injection of surface grout at the center of vein along the vein strike with radius 2.5 meter. It improves crown pillar recovery from previous analysis with the rock support as countermeasure method where 10 meter thickness crown pillar needs to be spared.

Application of surface grout is more beneficial than sill pillar since it can give higher recovery. However, it can only be applied if the ore grade is quite high and it is allowed by the government through environmental impact analysis to installed grout at surface of protected forest. Simulation with reduction of surface grout area is carried out to see the possibility to minimize its impact at surface of protected forest. The results show that there is possibility to reduce the grout area by using 5 m spacing or 1.25 m radius while keep having the same minimum crown pillar thickness. If the yield zone covers a large area, it is worthwhile to try grouting at the center of the yielded zone to have an obvious effect rather than grouting the entire yielded zone.