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FUNDAMENTAL PRINCIPLES OF ROCK FRACTURING AT THE VICINITY OF PRECONDITIONED BLAST HOLE

A simple empirical study on the orientation, diameter, and extent of radial fractures (long and short) at the vicinity of the face-perpendicular preconditioned boreholes is described. Homogenous and heterogeneous mining faces were considered when studying the orientation of radial fractures, four and five face-perpendicular preconditioning practices were used to investigate the outspread and diameter of radial fractures from one blasted drill hole to another. Long radial fractures were observed to be developed along the direction of the maximum principal stress and short radial fractures were observed to be developed along the direction of the intermediate principal stress in a homogenous mining face. On the other hand, long radial fractures were observed to be developed along the direction of the intermediate principal stress, while short radial fractures were observed to be developed along the direction of the maximum principal stress when the mining faces subjected to heterogeneous rock mass. The diameters of the radial fractures observed were inconsistent and were not nine times the diameter of the original borehole. Furthermore, the extent of radial fractures from one borehole to another was noted to be gradually improved when the additional of preconditioned borehole was in place. This study maintained that the orientation of radial fractures is mostly controlled by the rock properties, however, extend and the diameters of the radial fractures are controlled by rock properties, the effectiveness of the stress wave and gas pressure and brittleness of the rock mass.

Keywords: Radial fractures, Face-perpendicular preconditioning, Heterogeneous rock mass, Homogenous rock mass, Orientation of radial fractures

1. Introduction

The understanding of rock fracturing and, rock behavior and different conditions has been one of the common challenges faced by rock engineers (Sengani, 2020). In the meantime, studies on rock fracturing have been continuously reported in the past within several studies such as

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Obert & Duval, (1949); Hino, (1956); Duval and Atchison, (1957); Rinehart, (1958); Ash,(1963); Langefors and Kihlstrom (1963); Starfield, (1966); Porter and Fairhurst, (1970); Persson et al., (1970); Kutter and Fairhurst, (1971); Field and Pederson, (1971); Lang and Favreau, (1972); Bhandari and Vutukuri (1974); Hagan and Just, (1974); Barker et al., (1978); Winzer et al., (1983); Margolin and Adams et al., (1983); McHugh, (1983); Brinkmann (1987); Daehnke et al., (1996); Nie and Olsson, (2000); Sengani, (2020). The complexity of rock mass behavior under the effect of stress waves, gas pressure and geological discontinues has led many scholars to investigate the fundamental principles behind the development of rock fracturing using explosives. Their attempts were based on laboratory tests (Erdogan & Sih, 1963; Williams, 1957; Worsey et al., 1981; McHugh & Keough, 1982; McHugh, 1983; Sigh & Sastry, 1986; Horii & Nemat-Nasser, 1986; Schatz et al., 1987; Bhandari & Badal, 1990; Papadopoulos, 1993; Daehnke et al., 1997; Ayres et al., 2000; Olsson et al., 2001; Yang et al., 2013a,b; Yang et al., 2014) numerical approach (Kutter & Fairhurst, 1971; Rossmanith et al., 1996; Donze et al., 1997; Cho & Kaneko, 2004; Ma & An, 2008; Wang et al., 2009; Wang & Konietzky, 2009; Handi et al., 2009; Saiang, 2010; Bai et al., 2013; Onederra et al., 2013; Wei et al., 2016a-c) and observational point of view or empirical or field studies (Bhandari, 1979; Brinkmann, 1987, 1990; Liu & Katsabanis, 1996; Olsson et al., 2001; Lu et al., 2012,).

Almost all the previous scholars (Kutter & Fairhurst, 1971; Bhandari, 1977; Clark, 1987; Fourney, 1983) have indicated that rock breakage and rock fracturing usually occurs when explosives are confined in preconditioning boreholes and detonated, therefore a high-speed compressive radial strain wave is generated. The strain wave is then expected to travel outwards from the borehole in the rock unit, by so doing, rock particles/fragments are expected to move radially outwards resulting in tensile stress in the tangential direction. Where this tensile stress is greater than the tensile strength of the rock, radial stress fractures are expected to be developed. As the stress wave propagates outwards through the rock, the stress wave is followed by high-pressure gas associated with the reacting explosive. This gas expands and penetrates the cracks caused by the stress wave. The cracks then extend until the gas pressure drops below the critical level required for propagating the fractures. Nevertheless, the rockmass damage along the boundary of the borehole is controlled by the rock mass stiffness properties, temperature, velocity of detonation, amount of gas produced, borehole volume and many more (Saharan, 2004).

To date the fundamental principles behind rock fracturing at the vicinity of the blast hole/ preconditioned holes have been based on either laboratory tests or numerical simulation, however, few studies validate the simulated or tested results in an underground situation. Besides the above shortcoming, almost all the known study concerning the orientation, diameter, and extent of radial fractures at the vicinity of blast hole are based on the assumption that the rock mass is homogenous which is not always the case in an underground situation. There have been several suggestions concerning the actual diameter of the short radial fractures at the vicinity of the blast hole, such a large number of suggestions have usually provided confusion to the reader and mining house when it comes to the identification of an appropriate standard to follow as to verify an effective blasting.

Similarly, there are also several suggestions made concerning the extent of radial fractures at the vicinity of the blast hole, again most of this suggested has been reported noted to be unrealistic in a real situation. The above limitations have motivated the present study to perform a simple empirical study with the focus on addressing the actual behavior of the rock mass when subjected to blasting by explosives, therefore orientation, diameter, and extent of radial fractures are fully studied in this paper based on observational point of view.

2. The theoretical background of rock fracturing at the vicinity of blast hole

The use of explosives in rock breaking and initiating fractures on the rock mass have been documented to be one of the oldest concepts that explain rock fracturing in hard rocks (Kutter & Fairhurst, 1971, Winzer & Ritter, 1980, etc.). Nevertheless, the effectiveness of this concept is known to be controlled by proper selection of explosives, blasting devices, appropriate drill hole pattern design, appropriate blasting delay sequence. (Winzer & Ritter, 1980). There are several numbers of theories that govern the understanding of the fundamental principles of rock breakage and fracturing, which are well established in studies such as Winzer and Ritter (1980); Anon (1987). These theories revolve around two mechanisms which are; “the roles of stress waves generated from the explosive detonation (shock) force” and lastly, “the role of borehole pressure created by the detonation gas products”.

The effect of stress waves

The fundamental understanding of how explosives generate the stress waves has been fully documented in studies such as Kutter and Fairhurst (1971), Rinehart (1975), Mohanty (1985). Their studies have documented that shock waves are generated and travel quickly in the rockmass close to the borehole; however, these waves usually turn to decay quickly in pressure amplitude and dispersing in shape as the wave propagates away from the borehole. Nevertheless, this wave has been documented to carry both radial and tangential stresses components as they propagate. In simple terms, the rock unit closer to the drill hole usually experience high compressive stress which automatically exceeds the dynamic compressive strength of the rock unit at the vicinity of the drilled hole, nonetheless, the rock unit is therefore expected to experience shearing within the crush zone. At a small distance from this zone rock unit experience slight impact as compared to the crush zone, therefore as results, radial fractures or radial cracking occur in this zone.

These radial fractures usually developed as the rock falls in tension, but as soon as the tensile tail falls below the tensile strength of the rock unit then the fractures cease, and waves generally travel radially away as an elastic sound wave (Anon, 1987; Kutter & Fairhurst, 1971, Barker, 1978a and 1978b). In summary, Siskind and Fumanti (1974) and Anon (1987) contested that the radius of the crushed zone ranges from 2 to 4 of the drill hole radii and the fracture zone averages 20 borehole radiuses away and extends to 50 radii away.

The Effects of Gas Pressures

Researchers such as Porter and Fairhurst (1970), Langefors and Kihlstrom (1978) indicated that immediately after detonation takes place, certain gas products are formed so-called drill hole pressures. This gas is known to cause the extension of radial cracks if it’s enough to initiate the process. On the other hand, researchers such as Kutter and Fairhurst (1971) contested that this pressure only promotes heaving, in which heaving helps in muck pile placement due to opening the internal surfaces of which have been preconditioned by the stress waves. Nevertheless, Hagen (1977), Chiappetta et al (1983) have performed high-speed photography to understand the fundamental principles behind this behavior, the study indicated that fragmentation that took place during gas-driven is heaving of rock thrown from the bench. Winzer and Ritter (1980), had a different view, in which the authors argued that stress wave trapped in detached blocks promote the increase in fragmentation.

2.1. Previous studies supporting the successfulness of rock fractures by explosives

Kutter (1967) is one of the first known studies that have striven to complete the fundamental principles behind the understanding of rock fracturing at the vicinity of the blast hole using explosives. Kutter, (1967), investigated the role of stress waves and gas pressure in the fracture initiation process of an underground explosion. Well, the focus was revolving around boundaries of the blast holes, mostly preconditioned boreholes. As result, the author has reported that the stress wave is to generate densely radially fractured zone in the vicinity of the blasted borehole, on the other hand, the scholar also indicated the gas pressure exerted against the walls of highly fractured cavity usually generates quasi-static stress field. The quasi-static stress field was noted to cause further extension of radial fractures (long and short), where the longest cracks would extend first and extension of two opposed radial cracks would be favored. Kutter, (1967) also concluded that the high-pressure gases which are generated during blasting play a considerable role in the generation of radial fractures near the borehole, but gas pressure alone would not be sufficient in order to make it sufficient, the borehole needs to be preconditioned. The suggestion of preconditioning the borehole was based on the concept that it will help to open the pre-existing fractures within the rock mass and effectively widen the cavity and makes it possible for the expanding gases to be fully utilized in rock fragmentation.

Therefore, laboratory experiments involving high-speed photography and polymer have been used extensively to investigate mechanisms of dynamic fracture in 1970. The first well-known study to revisit the shortcoming mentioned above was by Person, (1970), the author used high-speed photography in conjunction with scaled model blasts performed in blocks of glass and acrylic as to observe the evolution of fractures from charged boreholes. Person (1970) has found that two predominant crack systems which include, radial cracks initiated near the borehole or spalling cracks initiated as tensile fractures caused by the reflected stress wave.

In 1971, Kutter and Fairhurst performed a theoretical computing study to provide clarity on the respective roles of stress waves and gas pressure in the rock fragmentation and fracturing. The study has indicated that the fracture pattern generated by stress wave are denser, with radial fractured zone at the immediate borehole vicinity, followed by a ring of widely spaced radial fractures. The study also found that the "diameter of the fractured zone was found to approach six-hole diameters for a spherical charge and nine-hole diameters for a cylindrical charge". Further, conclusions from the study have shown that that "cracks have a preferential growth orientation in the direction of the maximum principal stress of superimposed stress fields and the cracks pointing towards the free surface are longer than those pointing away from it". Finally, the study concluded that at high loading rates, the fracture pattern in Plexiglas appears to be practically identical to that of the rock mass, however only the scale and the length of the cracks differ.

There have been several studies conducted to improve or validating the conclusion drawn by Kutter (1967), Such studies include those of Schocky et al., (1974); Hagan and Just, (1974); Dally et al., (1975); Dally et al., (1976); Fourney and Dally (1975); Dally and Fourney (1976); Liu and Katsabanis (1996); Bohli (1997); Carrasco and Saperstein (1977); Bhandari (1979); Fourney et al (1981&1983); McHugh (1983); Young et al., (1986); Wang et al., (1990); Brinkmann (1987 &1990); Dojcar et al., (1996); Zhang et al., (2001); Olsson et al., (2001). A short discussion of some of the above-mentioned scholars is outlined below.

In Bhandari and Vutukuri (1974), the bench blasting parameters were studied to evaluate the understanding of rock fragmentation and rock fracturing. The experiment involved the use of granite blocks with the following dimension: 300 mm × 300 mm × 230 mm, the bigger mortar blocks were then blasted using detonating cord of 5.3 g/m with a borehole with a diameter ranging from 4.8 mm to 7.9 mm. The results of the research have shown that fractures at the vicinity of the blast hole are generally formed by quasi-static gas pressure and fractures near the free face noted to be formed due to stress wave's reflection. In simple terms, the research did not differ from the initial study by Kutter (1967). Nevertheless, the study by Brinkmann (1987 and 1990) has provided further clarity in which the author has reported that rock break-out is generally controlled by gas penetration and fragment size is controlled by shock waves.

Dally et al., (1975) have investigated the effect of gas pressure on crack generation using a laboratory study. The authors have used 70 mg of PbN6 to blast holes in 0.344" in which the blasted holes were made transparent in Homalite 100 2D sheets. Nevertheless, some of the holes were contained for the comparative gas pressure effect. The results of the study have indicated that gas pressure contributes much to extending cracks in the vicinity of the blast hole. While containments of gas products have been reported to increases the amplitude of tensile wave which then produces more fractures and fractures length. Lastly, the study argued that no difference was noted in compressional waves. This study has shown little or less disagreement with the study conducted by Bhandari and Badal (1990), in which the authors have concluded that reflected tensile wave influence the extent of fractures which have been already created by compressive waves, which implies that compressional wave has a role in fracture generation.

Furthermore, in 1979, Bhandari, conducted a pilot field study with the purpose to critically evaluate the effect of quasi-static gas pressure on rock fragmentation. In this study, several boreholes with a diameter of 25 mm were blasted with slurry explosives (0.5 kg/ per hole) on a 1 m high benches with granite as country rock. The spacing and burden were varied as common practice. The results of the study have indicated that the changes in blasting parameters were found to influence the change in rock fragmentation mechanism from the quasi-static gas pressure to strain energy. Owing to that the study by Bhandari (1979) seem not to fully agree with one of the initial conclusions made by Dally et al (1978), in which the authors have shown that regardless of the spacing of borehole and burden, but notched holes are appropriate in controlling the extent of fractures as compared to simultaneous firing and dummy hole practice. This implies that notched holes are the best when comes to fracture initiation and direction.

Worsey et al. (1981) had also conducted one of the crucial studies concerning cracks or fracture development in solid material due to quasi-static gas pressure and investigating the mechanism behind the pre-splitting of fractures. The study has used 25 mm diameter holes for 150 mm × 150 mm × 75 mm Plexiglas blocks with the detonating cords of 2.5 mm. This experiment was studied on sandstone blocks with discontinuous planes. The study has indicated that most of the cracks were exclusively caused by quasi-static gas pressure. The authors believed that the pre-splitting was primarily caused by the interaction of tensile stresses which were induced by quasi-static gas pressure. The conclusions outlined by the above-mentioned authors correspond very well with studies such as Daehnke et al., (1997); Olsson et al., (2001). A slightly different view was reported by Liu and Katsabanis (1996), in which the authors have indicated that air-decked has a large influence on the initiation of radial fractures, the study concluded that air – decked hole generally produced larger crater with large radial cracks at the vicinity of the blast hole.

The recent study by Yang and Ding (2018) on "fracture mechanism due to blast-imposed loading under high static stress conditions" has used a dynamic static experimental loading device as well as the digital laser to study fracture mechanism. Their study has reported that under the loading of initial static stress, a stress concentration is generated at the vicinity of the borehole, with maximum tensile stress generated in the position of maximum principal stress on the borehole. Further conclusions from this study are exactly what Kutter and Fairhurst have concluded. The study also evidences the understanding of rock blasting is very complex therefore laboratory and numerical approaches are the common technique to be used.

3. Research Approach

The analysis of the orientation, diameter, and extent of radial fracture was studied based on the observational point of view. Two face-perpendicular conditioning practice (four and Five) were used to compare the extend of radial fractures from one preconditioned blast hole to another along different mining faces. Furthermore, the orientation of radial fractures (long and short)

TABLE 1

Blasting Designs

Description	Diameter (mm)	Length of the hole (m)	Number of holes
Cut Holes	43	2.8	9
Perimeter Holes	43	2.8	26
Blast Holes	43	2.8	32
Pre-Conditioning Holes	51	4.3	4
Easers	102	2.8	4
Total Holes			75
Total Drilling Metres (Excluding Pre-con and Easers)			187.6
Total Reaming Metres			11.2
Total Pre-conditioned Metres			17.2

TABLE 2

Blasting parameters

Constant Parameters	
Description	**Design/Quantity**
End Width (m)	5.0
End Height (m)	5.5
Advance per Blast (m)	2.5
Rock Density (t/m^3)	2.71
Emulsion Density (t/m^3)	1.15
Explosives	
Description	**Quantity**
Blast Volume (m^3)	68.8
Blast Volume(t)	186
Charging Volume (m^3)	0.24
Emulsion Mass (kg/face)	280
Powder factor (kg/m^3)	4.1
Powder factor (kg/t)	1.5

was studied along several mining faces in which two cases were presented; 1. Mining face with homogenous rock mass and 2. Mining face with heterogeneous rock mass. These two cases were used to further the understanding of the orientation of radial fractures and used to identify if the rock properties have the impact of the orientation of radial fractures. Lastly, the diameter of the blasted precondition drill holes was considered and fully studied. Table 1 and Table 2 present the blasting parameters, as well as the dimension and sizes of the boreholes and explosives parameters used for the study. Figure 1and Figure 2 indicate the two face-perpendicular preconditioning practices within a production mining face.

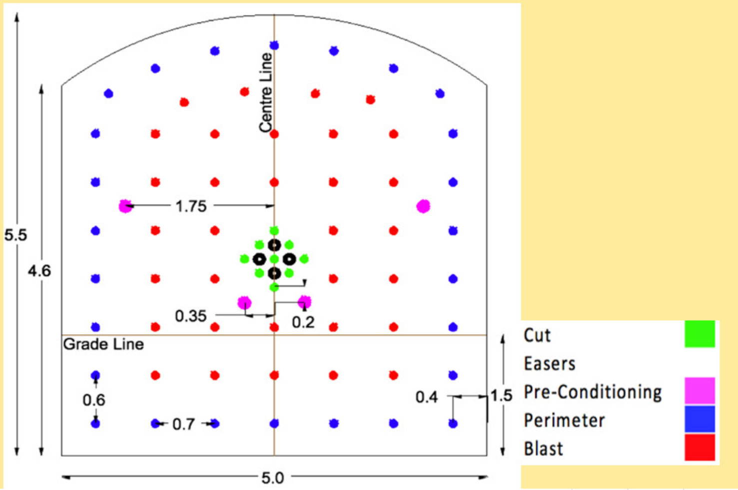

Fig. 1. Schematic view of fully drilled mining face with Four-face perpendicular preconditioned practice

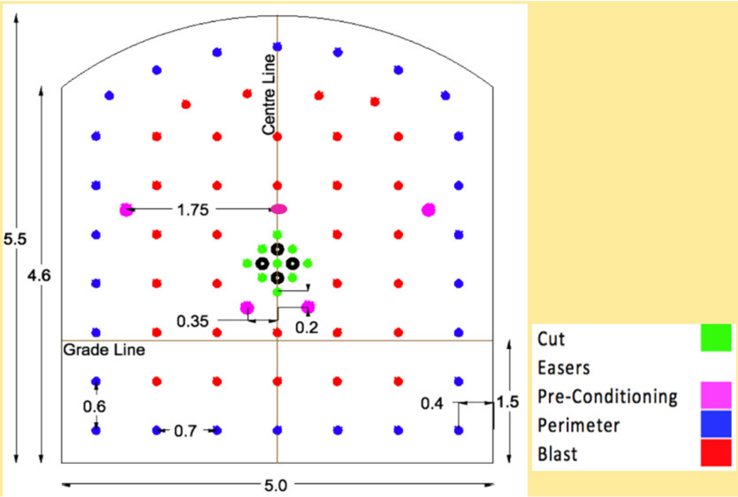

Fig. 2. Schematic view of fully drilled mining face with Four-face perpendicular preconditioned practice

4. Results and discussion

The results presented in this paper are divided into several sections, the first section presents and discuss the results of the orientation of radial fractures at the vicinity of preconditioned blast hole, second sections provide results and critical discussion on the developed diameter of radial fractures at the vicinity of the preconditioned blast hole and the last section provide results and discussion on the extent of radial fractures from one preconditioned blast hole to another. The results and discussion of the study are outlined in the subsections below.

4.1. Orientation of Radial fractures

The first case study was to look at the orientation of radial fractures when the mining face consists of one rock type or one reef. The second case study was to focus on the extend of radial fractures from one blasted precondition drill hole to another, and lastly, the research was also evaluating the diameter size of the blasted drill hole.

4.1.1. Orientation of Radial fractures in a Homogenous Rock Type

From the observational point of view, the orientations of radial fractures (long and short) in the vicinity of face-perpendicular preconditioning holes were found to follow a certain pattern in a homogenous rock type. Long radial fractures were observed to be well developed along the direction of the maximum principal stress, with short radial fractures observed to be spreading out along the direction of the intermediate principal stress. The schematic view of the orientation of radial fractures is denoted in Figure 3 and the actual observations of these conditions are denoted in Figures4 and 5. In simple terms, long radial fractures were observed to be developed along the hangingwall and footwall of the blasted preconditioned borehole, with short radial fractures observed to be well developed on the sidewalls of the blasted preconditioning boreholes. The results from these case study correspond very well with most of the previous studies in this topic, such studies include but not limited to: Obert (1962); Kutter (1967); Person (1970); Kutter and Fairhurst (1971); Rinehart (1975); Winzer and Ritter (1980); Mohanty (1985); Schatz et al., (1987a,b); Daehnke et al., (1997); Donze et al. (1997); Jung et al., (2001); Yang and Ding (2018). As already outlined in the literature body, the above scholars believed that longer radial fractures/ long cracks are always developed in the principal stress direction while short/few cracks/radial fractures are always developed along the direction of the intermediate principal stress. Their belief is actually based on the concept that when a rock mass is subjected to an initial static stress load, several stress concentrations are excepted to be generated at the vicinity of the borehole and the maximum tensile stress are therefore initiated along the maximum principal stress direction of the borehole which in turns to develop long radial fractures along the maximum principal stress direction while short radial fractures turns to be developed along the intermediate principal stress. Nevertheless, this first case study has validated the concept behind the orientation of radial fractures in the vicinity of the blasted preconditioned holes in high-stress conditions. This case study alone could not certify the conclusion behind the fundamental principles revolving around the orientations of radial fractures although the previous studies seem to focus on homogenous rock mass. Therefore, a second case study which involves heterogeneous rock mass was then considered, the discussion is outlined in the following subsection.

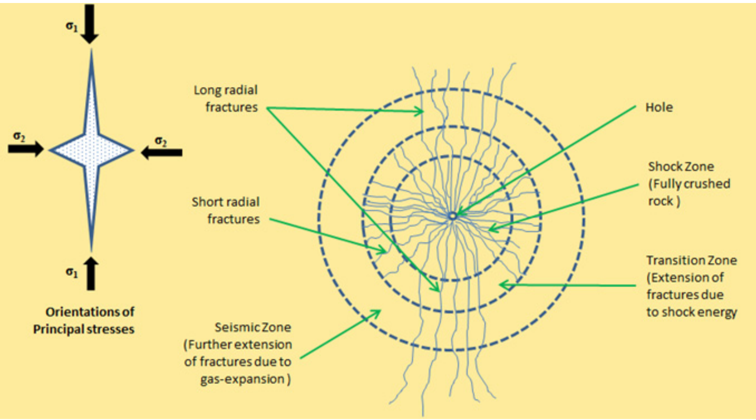

Fig. 3. Schematic view of the orientations of radial fractures in the vicinity of face-perpendicular preconditioning holes

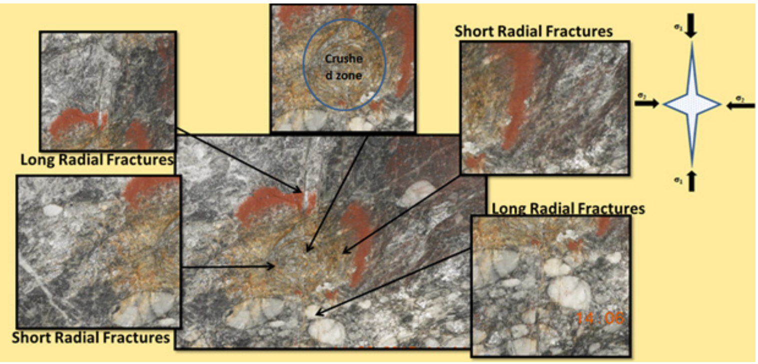

Fig. 4. The orientation of radial fractures at the vicinity of preconditioned blast hole in a homogenous rock mass

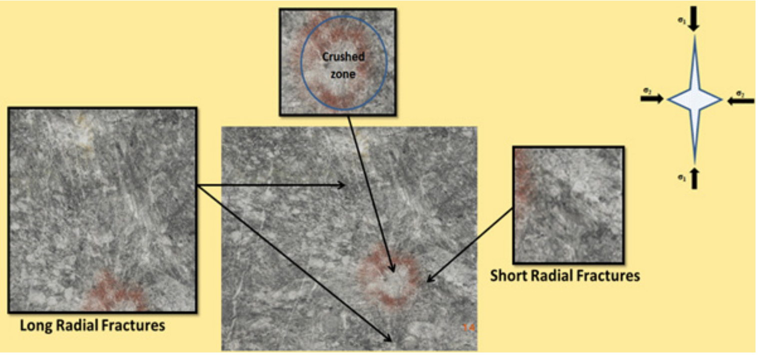

Fig. 5. The orientation of radial fractures at the vicinity of preconditioned blast hole in a homogenous rock mass

4.1.2. Orientation of Radial fractures in a Heterogeneous Rock Type

The second case study has shown slightly different results as compared to the first case study. The observational point of view has shown that the orientation of long radial fractures was observed to be fully developed along the sidewall of the boreholes, and along the direction of the intermediate principal stresses (see Fig. 8). On the other hand, short radial fractures were then observed to be fully developed along the hangingwall and footwall of the blasted preconditioned holes and along the maximum principal stress direction (see Figs 9-11). Figures 9, 10 and 11 indicate the observations made in different mining faces. Nevertheless, the results of this case study disagreed with all known previous work (Obert, 1962; Kutter, 1967; Person, 1970; Kutter & Fairhurst, 1971; Rinehart, 1975; Winzer & Ritter, 1980; Mohanty, 1985; Schatz et al., 1987a,b; Daehnke et al., 1997; Donze et al., 1997; Jung et al., 2001; Yang & Ding, 2018) conducted on this topic. This gives the impression that the fundamental principles behind the orientation of radial fractures outlined by Kutter 1967, Person 1970 and Kutter and Fairhurst 1971 and Yang and Ding, 2018 and others might be applied in homogenous rock at high-stress conditions. This belief was raised after several observations that have been made in both homogenous and heterogeneous rock types. Suppose, a mining face consist of multiple layered rock type (bedding planes), has

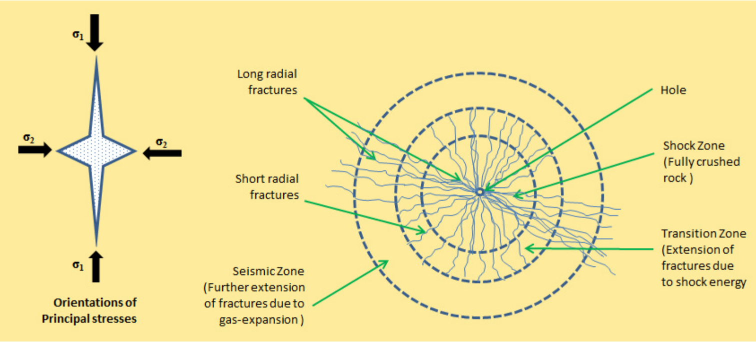

Fig. 6. Schematic view of the orientations of radial fractures in the vicinity of face-perpendicular preconditioning holes

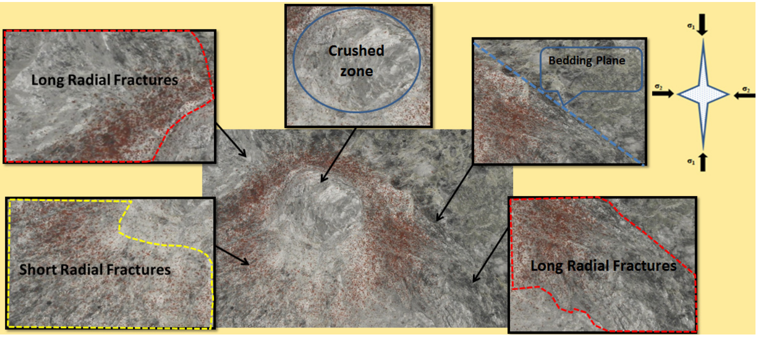

Fig. 7. The orientation of radial fractures at the vicinity of preconditioned blast hole in a heterogenous rock mass

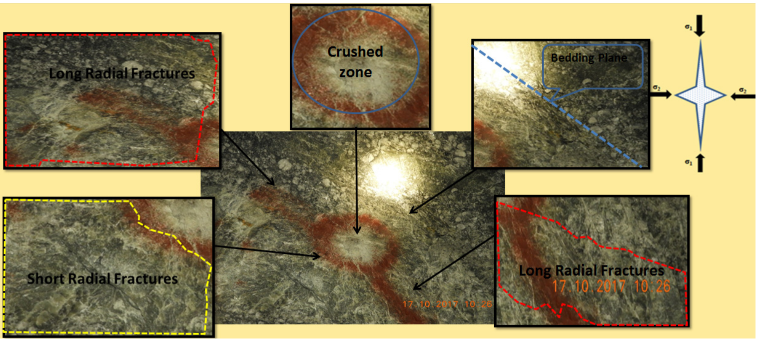

Fig. 8. The orientation of radial fractures at the vicinity of preconditioned blast hole in a heterogenous rock mass

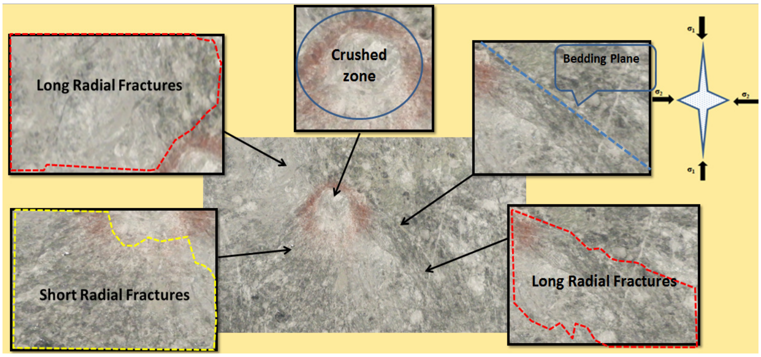

Fig. 9. The orientation of radial fractures at the vicinity of preconditioned blast hole in a heterogeneous rock mass

been observed to influence the orientation of radial fractures greatly rather than homogenous rock in which most of the known previous scholar assumed that the rock mass is homogenous. Although the homogeneous of the rock mass been assumed, the result of the studies could not be able to solve realistic situations. The results of this case study also create a useful argument that the orientation of radial fractures cannot be easily assumed based on static stress load and blasting stress only as per Yang and Ding (2018) and could not be assumed based on homogenous rock mass or material as per Kutter and Fairhust (1971), Obert (2001), because most underground situations are not homogenous. Therefore, factors such as rock properties mostly geological media must be considered as they have a great contribution to the orientation of the radial fractures.

4.2. The diameter of radial fractures at the vicinity of preconditioning holes

The diameter of short radial fractures at the vicinity of the blasted preconditioned borehole was also studied. The results of the study have shown that the diameter of the short radial fractures was not constant (see Figs 10(a-d)), however, none of the boreholes were noted to produce the proposed diameter of the short radial fractures by Kutter and Fairhust (1971). Kutter and Fairhust (1971) contested that *"the diameter of the fractured zone was found to approach six-hole diameters for a spherical charge and nine-hole diameters for a cylindrical charge"*. Regardless their (Kutter & Fairhust, 1971) conclusions, Schatz et (1987a and 1987b) has argued that the typical length of 10 times the borehole radius has extreme possibility to be achieved, the author further the argument by resisting the point that the fracture lengths of up to 50 times the borehole radius in a plane perpendicular to the principal stress direction are not inconceivable. In simple terms the results from this study do not correspond to any known studies concerning this topic; however, the study believed that the diameter of the radial fractures is mostly controlled by the rock type properties and effectiveness of the blasting practice in place. In supporting that, it was observed that different types of reefs (gold-bearing rock "conglomerate") develop radial fractures differently, in which large pebbles conglomerate usually developed short diameter of radial fractures while small pebble type of conglomerate develops large diameter of radial fractures (see Figs 10(a-d)).

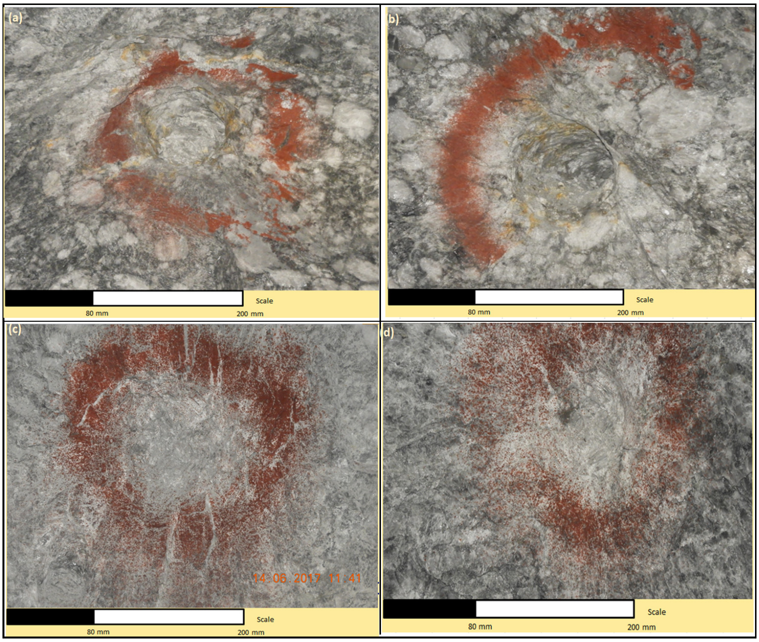

Fig. 10. The diameter of short radial fractures in the vicinity of the preconditioned blast hole

4.3. Extend of Radial Fractures along preconditioning holes

It was also found crucial to understand the fundamental principles behind the extend of radial fractures from one blasted preconditioning drilled hole to another. During the investigation, it was found that rock fracturing along the mining faces was in a form a spider web structure, the spider web structure was noted throughout regardless of the practice. To unfold the results of the research, the spider web structures were noted to be concentrated at the vicinity of each blasted preconditioning hole and could not connect from one blasted preconditioned drilled hole to another (see Fig. 11) during four face perpendicular preconditioning practice. It was also observed that the density of radial fractures was very poor along some of the mining faces. It appears that the development and extension of radial fractures are directly controlled by the rock type properties. The observations made correspond very well with some of the previous contributions made by Person (1970); Kutter and Fairhurst (1971); Siskind and Fumanti (1974); Rinehart (1975); Mohanty (1985); Anon (1987). Further studies by Winzer and Ritter (1980), Anon (1987) on rock breakage with the use of explosives has also outlined some of the cardinal points that radial fractures usually generate a spider web structure, but the extent of these fractures are controlled by the role of stress waves, gas pressure and the geology of the areas (rock types properties).

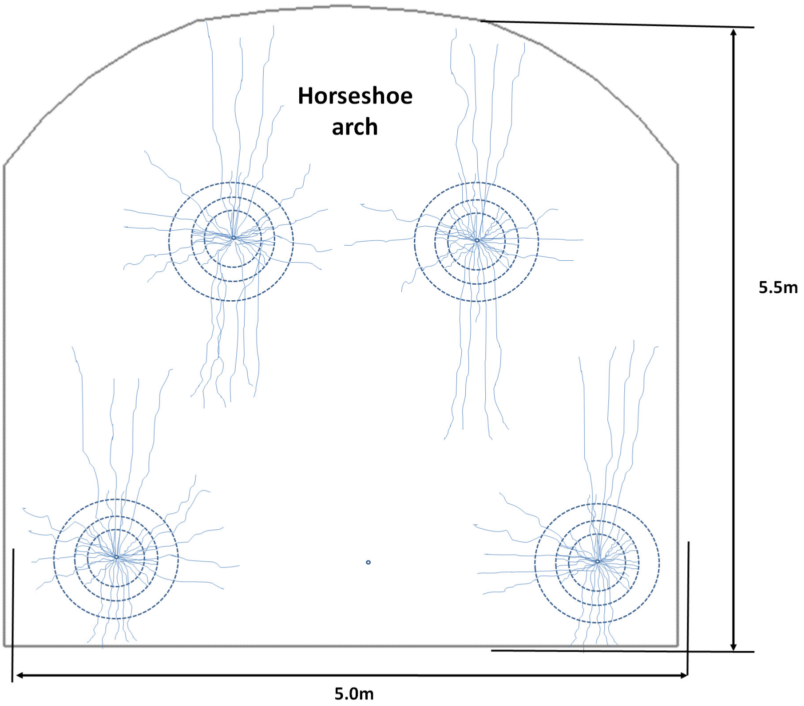

Fig. 11. Fracturing on the mining face during four drilled and blasted preconditioning holes pattern

These observations have then motivated this study to further the investigation on the extend of radial fractures along the preconditioned boreholes by improving or adding another preconditioning borehole, therefore five preconditioned boreholes were introduced on a similar mine dimension as four face perpendicular preconditioned practice. Nevertheless, this task was conducted to verify if the increase in several preconditioning holes influences the development and extension of radial fractures. The results of the study have shown great improvement in the extent of radial fractures from one borehole to another (see Fig. 12). There was a common behavior noted during the observations, it was observed that the extend of the radial fractures was still found to vary from different rock mass irrespective of the increase in several preconditioning boreholes (see Fig. 12). Nevertheless, the addition of one preconditioning borehole has shown that there is a gradual improvement in the extent of radial fractures from one borehole to another, but it was still impossible to give an exact diameter in which the radial fractures grow. These give the impression that it is very complex to quantify extend or the exact diameter of the radial fractures at the vicinity of the preconditioned boreholes.

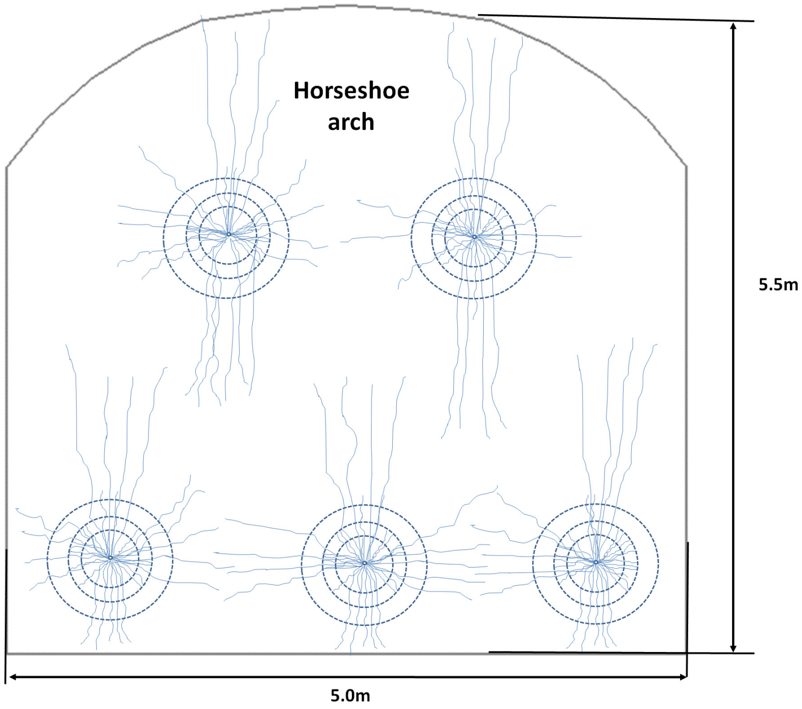

Fig. 12. Fracturing on the mining face during five drilled and blasted preconditioning holes pattern

5. Conclusions

Based on the results and discussions of the research, it was noted that the orientation of radial fractures (long and short) are mostly controlled by the rock properties. This conclusion was evidenced when comparing the orientation of radial fractures in a homogenous and heterogeneous rock mass, in which the research has indicated that the orientation of radial fractures found to support the previous work (Obert, 1962; Kutter, 1967; Person, 1970; Kutter & Fairhurst, 1971; Rinehart, 1975; Winzer & Ritter, 1980; Mohanty, 1985; Schatz et al., 1987a,b; Daehnke et al., 1997; Donze et al., 1997; Jung et al., 2001;Yang & Ding, 2018) when the mining faces are homogenous. It was also found that the orientation of radial fractures usually changes when mining faces are subjected to heterogeneous rock mass, nonetheless, this conclusion gives the impression that the orientation of radial fractures is control by the composition or properties of the rock mass. Based on the observational point of view, it was also noted that the diameter of radial fractures at the vicinity of preconditioned blasted holes were not constant either nine-hole diameter as per Kutter and Fairhurst (1971). The results of this research give the impression that there is no exact size of the radial fracture diameter, in simple terms, the diameter of radial fractures along preconditioned blasted holes cannot be similar through since fracturing depends on rockmass properties, blasting parameters and effectiveness of the blast. In supporting the above conclusion, the measured diameters of each preconditioned blasted were not closer to nine-hole diameters, in fact, most of them were very small. This gave the conclusion that the diameters of the blasted preconditioning drill holes are unique, and the uniqueness of the diameters is controlled by rock properties, stress waves, gas pressure and brittleness of the rock mass. Although previous studies such as Kutter and Fairhust (1971) and Schatz et al (1987a,b) has proposed certain standards, but the standards or estimated diameters seems not to be achieved in underground situations, however since most of these studies were numerical and laboratory studies, their results can be limited to the realistic of the actual situation in an underground environment.

It was also noted that the extend of radial fractures from one preconditioned blast hole to another is mostly controlled by the following factors: the number of preconditioned blast holes, the effectiveness of preconditioning blast, rock mass properties. Furthermore, it was also noted that although the increase in the number of preconditioned blast holes seems to influence the extent of radial fractures this factor has little or less impact as compare to rock properties and effectiveness of the preconditioning blast. In simple terms, rock properties and the effectiveness of the preconditioning blast play a major role in the development and extension of radial fractures. The study also suggested that a more sophisticated instrument can be implemented to find an appropriate approximation method that will be able to compare and match empirical results. It is also crucial to indicate that the obtained results might not be applicable in other brittle rock mass, which can be due to different rock types and different mining environment as well as the depth of mining and explosives or rock breakage mechanism used.

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