Quantifying unplanned fall of ground hazard in tunnel intersection and its implication for ground control in coal mines

by

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ORIGINALITY STATEMENT

I, Kaisa Nurailym, hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at Nazarbayev University or any other educational institution, except where due acknowledgement is made in the thesis.

Any contribution made to the research by others, with whom I have worked at NU or elsewhere is explicitly acknowledged in the thesis.

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ABSTRACT

The global economy still relies on coal. However, coal mines at time face operational problems such as fall of ground. Unplanned fall of ground in roadway intersections in coal mines present a serious threat to mine safety. Despite the technological and scientific advances in ground support, it is challenging to design the road intersections in coal mines due to variability of rock mass properties and the difficulties of obtaining reliable input data for the design, in most cases. Although, existing methods of design including numerical modelling or, empirical design approaches possess merits, they cannot properly handle these aspects above mentioned. Hence, it is essential to identify relationship between the unplanned roof falls, support methods, presence of water and the geology to create an expert system, which will be helpful for miners to contribute towards improving rock fall related safety in coal mines. Firstly, numerical modelling carried out with RS2 software, is employed to characterize selected cases of FoG in the database and to further validate an expert system. Secondly, an expert system via fuzzy logic (fuzzy inference system) is developed to allow to objectively handle qualitative parameters (which could be subjective) associated with the FoG in tunnel intersections. Data pertaining to roof fall in roadway intersections are compiled from US coal mines are used to calibrate and validate the newly proposed tools. The data include the size of the FoG, the geology, the coal seam characteristics, the types of support and the presence water. It is expected that the results of this study indicate good agreement with the filed. The end results (derived empirical tools) could be helpful for mining engineers in managing FoG in tunnel intersection in coal mine around the world.

ACKNOWLEDGMENT

I want to express my sincere gratitude to my supervisor, Professor Adoko Amoussou Coffi for his unwavering support and direction throughout the thesis-writing process. I am grateful for his meticulous attention to detail, persistence, and creative research ideas. Without his assistance, this task would not be possible.

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Chapter 1. Introduction

Introduction to the chapter:

This chapter provides general information about coal mining around the world and why FoG in underground mines is an important issue. Also, the aim and objectives, significance of this thesis for the industry.

1.1 Background

In recent decades, the coal industry has been crucial to the development of the energy sector and to the expansion of a nation's economy. Due to the ever-increasing demand for coal, coal mine operations are currently raising their targets. Coal mining will continue to be important in worldwide fossil fuel consumption in contrast to other forms of energy production due to its use in power generation, transportation, residential and commercial uses, as well as the fact that it is inexpensive to mine and easily accessible. Global demand for coal is still high despite increased knowledge of the environmental effects of the coal sector. As a matter of fact, global coal consumption increased by 0.7% in 2018, mostly due to growth in China, India, and Southeast Asia (V.B. Kondratyev 2019). Because of the importance of coal for instance in countries like Kazakhstan - economy’s as it is generates 74% of country’s electricity, produce 100% of its metallurgical or chemical coal for industries (Debo Adams 2019), in Australia's economy coal also produced 60% of the nation's power (Proctor April 1, 2022) so coal consumption will continue to be in demand for many decades. The mining sector in South Africa makes a significant contribution to the national economy. The overall revenue from primary resource sales in South Africa in 2001 was $13 billion, gold (31,90%) and coal (18,90%) were closely behind. The direct contribution of mining to GDP is about 7.5 percent, while the projected indirect contribution is 15 percent (Koldaş 2003). The current war between Russia and Ukraine, on the other hand, has wreaked havoc on the pricing and availability of coal to end users for commercial and industrial purposes, as a result, there is a chance that Kiev and other cities will not get any light (Ahmad 2022). In addition, as tensions relax as it attempts to replace supply from Russia, China, the world's largest coal user, has declared it may lift a nearly two-year ban on Australian coal. This demonstrates the significance of coal as an indispensable commodity, and therefore coal mining.

Nevertheless, some of the biggest issues connected with coal mining are safety and profitability concerns. Each year tens of thousands of intersections are driven in underground mines. Excavations near junctions are noticeably more likely to undergo FoG than excavations away from intersections. In contrast to intentional falling of rocks in some mining techniques, such as caving rock behind a longwall face, collapsing roof in a retreat room-and-pillar mine, or caving rock in a block-caving hardrock mine, FoG is defined as the unintentional falling of loose rocks from excavation faces (roofs and side walls). The term "fall of ground" refers to a type of accident that can occur in underground mines, particularly in areas where the rock or other material surrounding the mine openings is unstable or unsupported. Fall of ground occurs when a section of the rock or other material collapses or falls, either suddenly or gradually, creating a hazard to miners working in the area. This can happen due to a variety of factors, including natural geological processes, inadequate support structures, or mining activities that destabilize the surrounding rock. Falls of ground can be particularly dangerous because they can occur suddenly and without warning, and they can cause serious injuries or fatalities to miners working in the affected area. As a result, mining companies and regulatory agencies take extensive precautions to identify and mitigate fall-of-ground hazards in underground mines, including through regular inspections, geotechnical analysis, and the use of support systems like bolts, mesh, and shotcrete to reinforce the rock around mine openings. These include rock collapses, cave-ins, raveling, squeezing, slabbing, bursting, etc. from the roof and the sides/ribs of apertures that can be structural or stress-induced, which poses risks to the industry (Adoko 2017). There are several reasons of the ground failure like overspanned intersections, non-sufficient support, excess horizontal stress and weak geology with low strength of rock Intersection is exposed ground that could span 25-50 ft, over the normal width of an inlet. The stability of intersections depends on rock quality and the ratio of horizontal stress to vertical stress. Other secondary factors like quality of bolt installation, turnout frequency and location (Young, Walton et al. 2019). According to recent data, side fall and roof fall incidents made up, respectively, 21% and 13% of all fatal accidents in 2014 and 2015, according to a recent report in the USA, coal output steadily remains 1.0 billion per year with annual fatalities under 30 and mining fatality rate exceed other major industrial sectors. Most of the injuries and fatal accidents in coal mining is largely connects with weak enforcement, lack of safety awareness and fall of ground. Death rate in coal mining due to ground falls make up a large portion of this rate. It is reported that in 1998 from 827 underground mines that produced 380 million tons of coal, showed 790 injuries and13 fatalities due to falls of roof (Molinda 2008). In recent years, many people have lost their life in coal mine roof fall incidents at tunnel intersections in various parts of China. For instance, according to (Wang 2022) in 7 province of China, 69 miners would die from fall of ground between the years of 2017 and 2021, along with 4 injured and 11 individuals who are still missing. According to (Harris 2014) in countries like India and South Africa the amount of coal mining fatalities caused by fall of strata were twice time bigger than amount of fatalities caused by explosions between 2006 and 2010, 114 and 21 cases respectively. These examples of causalities show the need to investigate FoG occurrence and to propose tools to enhance ground control program.

1.2 Problem statement

Because of its importance, FoG has been investigated over the past few decades. There are many strategies being explored by researchers to enhance the engineering geological model of underground coal mines. These methods include rock mass characterization and empirical field measurements (Hanna 1991, 1995) detailed field measurements (Wang 2022); numerical modelling (Sonkar 2022). Although these existing methods have made a substantial contribution to our understanding of the fall of ground in excavation intersections it is still challenging (Mueller 2010). Especially, quantitative correlations between FoG and its influencing parameters (e.g rock mass, geology, presence of water in underground layers and support system's condition) are quasi nonexistent to provide designers with a full FoG characterization in coal mines. Thus, there is a gap in terms of designing ground support at tunnel intersections in a more reliable way. Those gaps are linked to data which used for designing of coal mine development. In most cases engineers uses subjective data and knowledge, which results in unintended ground instability. These factors are not considered by traditional design tools. Expert systems such as Fuzzy Inference Systems (Bazarbay and Adoko 2021) can be used to accurately assess the connection between unexpected roof falls, support techniques, and geology. In addition, numerical modelling can be used to simulate the FoG under different conditions. These two aspects will be addressed in this thesis.

1.3 Aim and objectives

Motivated by the existing problems as mention in section 1.2, the aim of this thesis is to develop an expert system capable of quantifying fall of ground (FoG) hazard in coal mine tunnel intersections. To achieve this aim, the main objectives of the research are:

1. To conduct a critical literature review and analyze previous studies done on fall of ground in coal mine intersections;
2. To describe the compiled FoG data and perform basic statistical analysis;
3. To carry out a parametric study to analysis FoG behavior in tunnel intersection using Rocsience software (RS2);
4. To establish an expert system for tunnel intersection with the purpose of quantifying the relationship between the FoG characteristics and its influencing parameters
5. To establish a Fuzzy Inference system (FIS) for FoG in coal tunnel intersection for with the purpose of relating "qualitatively" the FoG characteristics and its influencing parameters
6. To summarize, compare the main results and discuss their implication for ground support.

1.4 Project significance to the industry

Unplanned Fall of Ground (FoG) occasions are in the mining industry's interest because of mine safety and profitability. The successful completion of the thesis offers multiple benefits to the mining industry. First, based on an expert system miners can improve rock fall related safety in coal mines. Using the proposed approach, mine engineers can quickly figure out the needed support system type for certain ground properties. Second, miners can identify link between unplanned roof falls, support methods, presence of water and the geology and as a result there will be decreasing of the human (mining engineers) error. Moreover, mine engineers can evaluate the fall of ground using numerical modeling through FIS analysis link integrated into empirical design tool. Finally, tool could be helpful for mining engineers to manage and understand implication of FoG in tunnel intersection in coal mine around the world.

Chapter 2. Literature review

2.1 Main Coal Mining Types

Most of the world's coal reserves are in underground. Underground mining, also referred to as deep mining, is a method for removing coal from up to 300 meters beneath the surface of the Earth (1,000 feet). Miners use an elevator to descend a mine shaft to reach the mine's depths. Large gear is operated there to extract the coal and carry it above ground.

Main mining types of coal are room-and-pillar and longwall. In room-and-pillar mining type miners create a "room" out of coal using the room-and-pillar mining technique (Figure 1). The roof and overburden are supported by coal "pillars". The chambers are normally 9 meters (30 feet) wide, although the support pillars can be up to 30 meters (100 feet) wide. There are two types of room-and-pillar mining: conventional and continuous. Traditional mining uses explosives and cutting equipment. Continuous mining removes the coal using a sophisticated machine called a continuous miner (Geographic 2021).

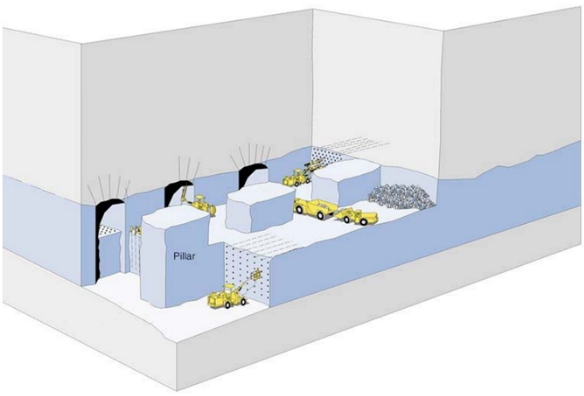

Figure 1.The classical room-and-pillar mining method (Zevgolis 2005)

The weight that the pillars on either side of the longwall panel support grows as the longwall panel in longwall mining travels forward and extracts coal (Figure 2). Additional yielding support (such as beams and cribs) is frequently required in these locations because of the exceptionally high pressures put on the pillars and the ensuing steep and occasionally uneven roof convergences(Mueller 2010) .

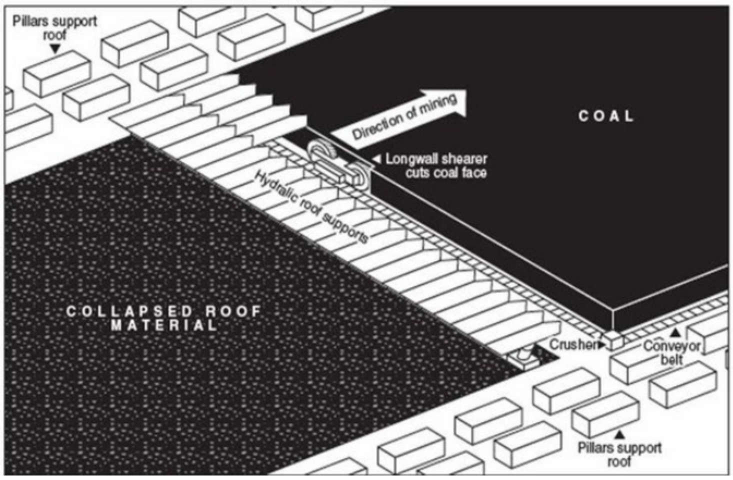

Figure 2.Depiction of longwall coal mining method (Saki 2016)

Coal is a flammable sedimentary rock formed of old flora that has been trapped underground for a very long time, between other rock strata. The process of carbonation, which is the underground conversion of vegetation to coal seams, heavily depends on physical factors like pressure and heat. The thickness of coal seams can range between a few millimeters to several tens of meters. It mostly comprises of carbon (50–98%), hydrogen (3–13%), and oxygen; nitrogen, sulfur, and other elements are present in lesser amounts. Liquid and small fragments of other inorganic materials are also present. Coal burns to provide energy in the form of heat, which has a variety of applications. The two main types of coal are brown and black, which have differing thermal characteristics and uses.

There are several differences between coal seams' geological characteristics, depth at which they are being mined, and regional and local geology. The presence of water and strong horizontal stresses may have an impact on the conditions on the roof in addition to the local geology. The deposits just above coal can range in size from huge thick layers of sandstone or limestone to strong laminated layers of siltstone and sandstone to tiny weak layers of (Jeremic 1985)

2.3 Main Causes of Roof Falls

During the mining process, there are several hidden dangers that might occur in underground coal mines, including roof falls, gas explosions, surface subsidence, and more. Roof fall is the most common and dangerous hazard, leading to injuries and fatalities, and is a major worry for underground coal miners, as seen in Table 1.

Table 1.Fatality distributions in coal mines per selected countries (Harris 2014).)

Country	Explosions	Strata fall	Explosions and strata fall
Australia	0	0	0
China	2145	188	2333
India	74	114	188
South Africa	3	21	24
USA	49	26	75

Each year, tens of thousands of intersections are driven in underground coal mines. Intersections show exposed land that can extend 25–50 feet, much beyond the typical entryway width. The greater spans can quickly become dangerous when pillar corners are softened to facilitate transit and when pillar spall exposes more roof (Gregory Molinda 1998). It has been shown that year after year there is a higher risk of failure intersections, and the majority of these cases are related to specific issues such horizontal stress and geologic discontinuities (Blevins C.T. 1985) Numerical modeling studies have confirmed that intersections are less stable than entries, In many mines, wire mesh must be fastened to the roof in order to stop the weak shale layer from cracking and failing gradually owing in part to weathering and lateral confinement. Intersection instability was found to be dependent on rock quality and the ratio of horizontal stress to vertical stress (Gercek 1982)

The two categories of collapse hazard variables are as follows: The first is geological - namely related to rock mass structure and properties of mineral. Second is mining and technical - related to the exploitation system and technology that primarily determines the size of workings, types of support, and distribution of stress. The fundamental engineering issue is how each aspect contributed to the collapse conditions and how to identify more hazards in the specific geological and mining settings. Experience has shown us that a wide range of combinations of variables may increase the risk of a roof fall (Małkowski and Juszyński 2021) According to (Gregory Molinda 1998) Much safer than room and pillar mining is longwall mining. Although longwall production is getting close to room and pillar mining levels, room and pillar mining has a much greater rate of roof falls. The National Institute for Occupational Safety and Health (NIOSH) has focused on this issue in a few its ground control research investigations. Significantly more intersections fall than non-intersections.

In the past, descriptions of the geology of mine roofs were quite detailed and needed analysis for use in engineering design and reinforcement choice. Rock examinations such as uniaxial compressive strength, the Brazillian indirect tensile test, direct shear, or triaxial tests have been used in more quantitative attempts to determine the strength of the roof. Small sample sizes are a problem for these tests, but more significantly, they don't capture the actual rock vulnerabilities. Applying existing rock mass classifications like RMR, URCS, RQD and Q system has also had mixed results.

The Bureau of Mines created the CMRR in 1994, and it has nowadays extensively utilized for many other things, like: stress modeling, chain pillar design, and roof hazard assessment. CMRR stands for Coal Mass Rating. It is a system used to assess the quality of coal based on its physical properties, such as density, hardness, and strength. The CMRR rating is used in the mining industry to estimate the amount of coal that can be extracted from a particular area or coal seam. The CMRR system assigns a numerical rating to the coal based on its properties. The rating ranges from 1 to 100, with higher ratings indicating higher-quality coal. A coal seam with a CMRR rating of 80 or above is considered to be of high quality and may be more profitable to mine. The CMRR rating system is just one of many factors that are considered when evaluating coal deposits for mining. Other factors include the depth and thickness of the coal seam, the quality of the overburden (the material that lies above the coal), and the accessibility of the site.

The fundamental tenet of the CMRR is that the faults or discontinuities, rather than the strength of the entire rock fabric, are what weaken or destroy the roof beam. The goal of the CMRR is to assess the roof discontinuities that most affect the strength and demise of the roof mass. The weak bedding planes, slickensides, joints, and laminations are highlighted (Figure 3).

There are two components to the CMRR system. First, by analyzing the discontinuities in the rock with straightforward field testing, the Unit Rating of each rock member in the bolted period is established. To ascertain the tensile strength of bedding, a chisel is hit parallel to the bedding.

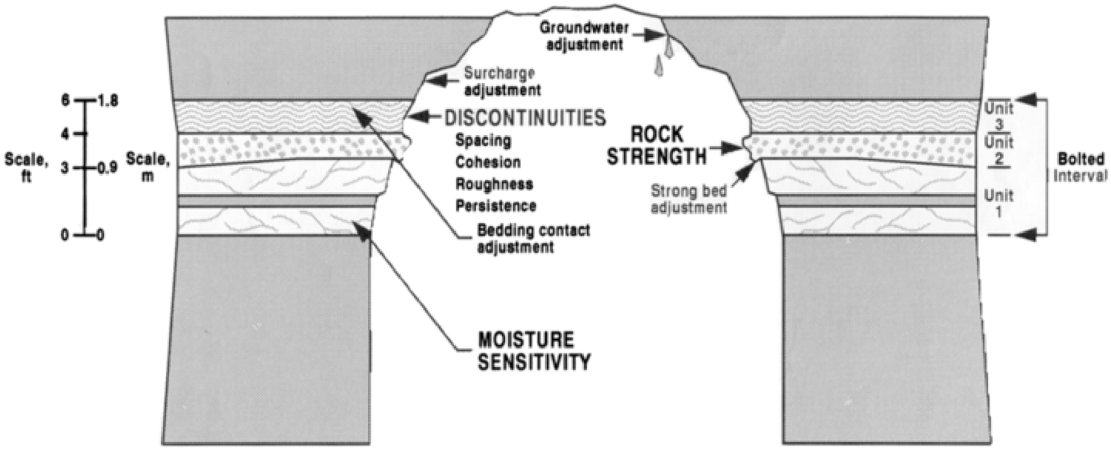

Figure 3.Components of the coal mine roof rating - CMRR

A ball peen hammer is used to produce an indentation scaled to the compressive strength of the rock matrix. Lower point values signify thin, closely spaced laminations or slickensides. The spacing and occurrence of bedding planes, joint sets, slickensides, and other discontinuities are given points. Points are deducted for moisture sensitivity and persistent discontinuities.

The measurement of the Roof Rating is the second component of the CMRR. The thickness-weighted average of the Unit Ratings is calculated, and unit affiliations are considered. Points are added for the existence of a solid bed in the bolted roof. The sturdy bed is one of the most significant ideas included in the CMRR.

Immediate roof geologies can be categorized into three categories, according to (Tang 1986). First, each layer deflects separately and at a greater rate than its underlying strata. The second is that certain strata deflect more than the underlying strata, and the third is that each stratum deflects more than or equally as much as its underlying stratum. The influence of axial loads brought on by horizontal tensions and a well-constructed roof fastening system are the two most crucial factors to prevent roof collapse.

There are spans that will cause entrance failure for any given geology. The important thing to remember is to stay within the permissible span, which is determined by the strength and roof reinforcement.

2.3 Stress Fields in Coal Layers

If horizontal and vertical stress fields are not adequately managed by pillar design, room spacing, entry orientation, and support design, they can lead to serious stability issues. The weight of the overburden above the excavation causes vertical stress magnitudes to grow with depth. Geographic position predominantly determines the magnitudes and orientations of horizontal stress, which can outweigh vertical stress by a factor of three or more, especially in shallower deposits. The amplitude and direction of horizontal fields, which can lead to issues like bed separation and roof buckling, are thought to be caused by plate tectonics. Researchers realized in the 1940s that a significant amount of the roof damage encountered underground was caused by substantial horizontal tension (Mark C. 2008).

Intersections may easily become overspanned if care is not taken when mining. When the rock is strong, small increases in span probably will not compromise the stability, but where the roof is weak, small increases in span can add significant load to the bolted interval above the intersection. If the geology is uniform, the rock-load height can be expected to be proportional to the span and to the roof rock quality, according to the equation 1 proposed by Unal:

$$h_t = (\frac{100 - RMR}{100})W_E \quad (1)$$

Where h_t=Rock-load height, ft;

RMR = Rock Mass Rating, which is equivalent to the CMRR

W_e=Entry width,ft.

According to this equation, a competent roof intersection with a CMRR close to 100 would have a very low rock-load height, but an intersection with an incompetent roof (CMRR close to 0) would have a rock-load height about equal to the span. Equation 1 may be simplified as follows, at equation 2 assuming that K can be used in place of the geologic correction factor, (100-CMRR/100):

$$h_t = (K)w_e \quad (2)$$

thus the rock-load height is proportional to the span. Assuming that the rock load above the intersection can be represented as pyramid (fig.5) the volume of rock and rock load over the intersection can be estimated by the equation

$$R_L = V_I\gamma = \frac{(w_e)(w_c)(h_t)}{3}\gamma \quad (3)$$

Where $R_L = Rock\ load\ above\ intersection,\ lb$

$V_I = Volume\ of\ rock\ above\ intersection, ft$

$\gamma = Unit\ weight\ of\ rock, pc$f;

$w_e = Entry\ width, ft; and$

$w_c = Crosscut\ width, ft.$

The rock load is proportional to the cube of the span if w_e=w_c in the majority of cases, as shown in equation (3), where w_e and K(w_c) have been replaced for w_c and h_t, respectively. The load is still proportional to the cube of the w e equation if it is assumed that the rock load above a junction can be represented by a cube (instead of a pyramid) (equation 4,5)

$$R_L = \frac{K(w_e\ )^3}{3} \tag{4}$$

$$R_L = K(w_e\ )^3\gamma \tag{5}$$

The actuality typically lies between these two idealizations, judging by the geometry of roof fall voids. In both situations, a slight increase in entry width (and thus, increase in intersection span) causes a noticeable rise in the rock load.

The rock load height may be constant independent of the junction span in geological conditions when the roof falls are terminated by an overlaying self-supporting strong bed. The rock weight in this situation rises proportionally to the square of the span (Gregory Molinda 1998)

To forecast impending intersection failure, roof strain monitoring has been used. In UK coal mines, the usage of early warning systems is required. Since the introduction of roof bolting and monitoring in British coal mines in 1991, the number of ground falls has been significantly reduced (Altounyan 1997).

The NIOSH Mine Safety and Health at Pittsburgh Research Laboratory did a project to study the factors which affect the stability of intersection. The roof fall rate in each of the mines was calculated based on the estimated amount of entry drivage. The entry drivage was calculated using the reported output, with seam altitude and longwall usage considered. The calculation considered the exact seam height. For instance, the mine with the greater seam would have a greater roof falls risk because of fewer drivage and far less exposed roof in identical mines with a same amount of roof collapses and same productivity. According to estimates, expansion amounts in longwall operations made up 1/4 of all yearly tons. As a result, the longwall mine fall rate became raised by 4. There is a relationship among CMRR and roof fall rate, according to previous experience at specific mines. As the CMRR grew, the frequency of roof falls dropped. The database's CMRR varies from 32 (extremely poor) to 75. (very competent).

A connection between CMRR and intersection span was discovered. In overall, the mean intersection span (sum-of-the-diagonals) grew as CMRR grew in the 12 mines in the database. This connection is impacted by elements including regional mining practices and roof protection. It might mean that miners' widths reflect the operators' knowledge from experience that a sturdier roof is better suited to hold a larger span.

According to the data from (Gadde, Rusnak et al. 2008) CMRR is carried out using an empirical strategy known as the ARBS. However, ARBS is only valid if the bolts function in beam construction or supplemental support mode.

2.4 Support system for roof of Coal mines

As the top of any underground mine is susceptible to collapse, several supporting systems are employed to keep the roof stable. The holding system consists of both standing reinforcements like lumber and intrinsic forces like roof bolts. They work alongside the ground to create a strong rock structure. Bolts, cable bolts, metal pins, and other items are inserted inside the roof as part of the instinctive support system. Standing support is a technique that uses components—wooden logs, metal rods, steel arches, timber and powered supports are positioned between the roof and floor. Given its low cost and ease of availability, timber supports are widely used in Indian coal mines. Timber-supported workings produce more than 90% of the underground coal. When the force operates parallel to the length of the timber prop, it is at its strongest. Iron and steel were utilized in mines as corrugated sheets, beams and girders, concrete reinforcement, and stiff and yielding props. The cutting machinery can be used to its full potential thanks to mechanized stabilizers, which can move forth quickly sufficient to keep up with any contemporary face cutter. They therefore permit the face to move quickly, which then in turn improves the circumstances of the rooftop at the face. The last is an intrinsic support types like : roof bolting, roof stitching, wooden dowel and bamboo bolting (M.Barcza).

In coal mines, roof fastening is a strictly necessary procedure known as main support since it takes place as construction is progressing. The system can aid in supporting the rooftop by offering skin control, suspension, or beam building, depending on the exact roof geology and the kind of bolt utilized. Local geology plays a major impact on choosing the bolt system required for support. The physical indicators like load bearing capacity, the density of bolting system and the size of the bolts all affect how much support a bolt system provides.

Mechanical anchors and completely resin grouted bolts are the two types of bolts most frequently employed in coal mines. Mechanical anchor bolts are used to connect the enormous rock layers above with the coal layers below (Figure 4). Because of the tensioned bolts at the base of the thin strata, the thin strata is essentially pinned to the enormous ceiling above. The two types of grated bolts are passive and active bolts. Mechanisms for tensioning and anchoring are where they diverge most. The first one is entirely grouted with resin cartridges and un-tensioned during installation. The second one was tensioned during installation and fastened using either a mechanical shell and resin or two speed resin. Thin individual rock strata were transformed into one large beam by grouted roof bolts that were completely fastened to rock over their whole length. According to National Institute for Occupational Safety and Health (NIOSH) at one time, mechanical anchor bolts were the main roof support and the main benefit is quick installation, less than 10 seconds. However, nowadays-mechanical bolts were displaced by fully grouted bolts (Figure 5). Mechanical anchor bolts were once the primary means of roof support, according to the National Institute for Occupational Safety and Health (NIOSH), and their main advantage is that they can be installed in less than 10 seconds. Modern mechanical bolts, however, were replaced by fully grouted bolts.

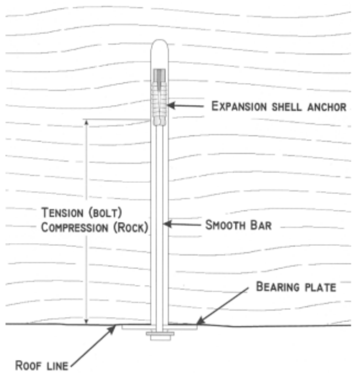

Figure 4.Mechanical anchored bolt installed in roof.

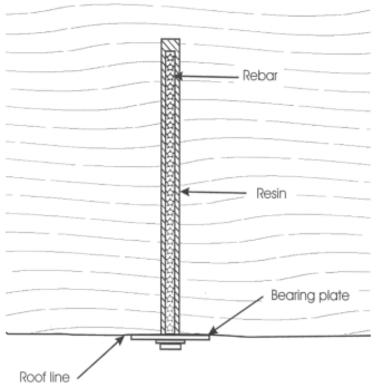

Figure 5.Fully grouted resin rebar installed in roof.

Bolt length indicators are more problematic for mechanical anchor bolts than fully grouted bolts, according to (Dolinar and Bhatt 2000). The fundamental cause of this is that resin bolts only need to be 60 cm long to reach their full support capacity. The length of the mechanical bolts must be sufficient to anchor in a solid foundation that could be 1.85 meters or higher above the nearby roof. In order to reinforce the contact area and anchorage to withstand the

increased bolt load, it may be advantageous to extend bolt length (mechanical) or rebar diameter to #6 (resin) in certain regions. The biggest bolt loads often happen at the center of the intersection.
In addition to the principal bolting system, cable bolts and truss bolts are frequently inserted in the roof as additional support types in ground control plans. A cable within the rock is connected to a bolt with an anchored end in rein that is normally 4 feet long and fixed to a ceiling plate. The technology for maintaining truss intersections that uses three-dimensional compressive pressures to sustain the entire intersection.

2.5 Coal roof deformation mechanism

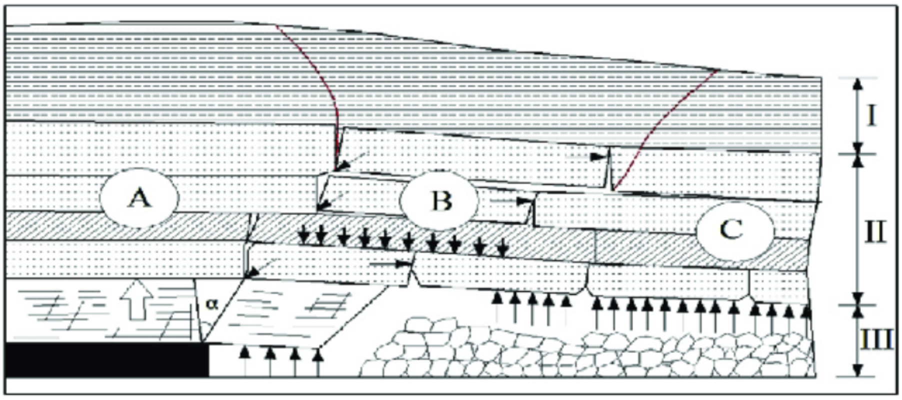

Figure 6. Beam Thory Model (He, Zhu et al. 2015)

The roof in Figure 6 is viewed as a single beam that is supported at both ends by the pillars. The weight of the roof itself and the thickness of the barrier determine the load on the roof. The weight of the balk exerts a vertical downward force as the load. A rock layer's stiffness and resistance to bending are frequently inversely correlated with its thickness and elastic modulus. Between the mine mouth and the surface, a portion of the rock layers will be less rigid than those above.
The rock strata are usually imagined to be held together by a single beam when entirely grouted roof fasteners are used. The units that split from the rocks above to form the beam may be imagined to be the thickness of the length of the roof bolts. Another possibility is that some of the rock strata above the roof bolt-formed beam are less rigid than the rock strata above, which would allow the strata above to relax and place additional stress on the beam on top of its

existing weight. Every time, the coal beneath them and the rock above the beam and over the pillars are portrayed as implacable and unyielding, forcing the rigid grasp on the ends.
The classic balk theory model considers that stress is driven by the downward pull of gravity. In fact, in underground we have also tectonic stress field that imposes compressive forces from the sides. Depending on the orientation of the entries and rooms, it is possible for the compressive forces to reduce the tension within the roof balk. These factors suggest that the balk model might not accurately reflect common modes of failure observed in the real world. When used to analyze junction failures, the beam model appears to be wrong in a number of ways since the area in cross section does not have an infinite length as the 2D model implies. Beam theory may be utilized for entry when the length of the roof is twice as wide, but when the length is less than twice as wide, as at intersections, the calculations for stress and deflection must be based on the Flat Plate Theory (Chugh 2009)
When roadways are excavated in underground coal mines, the laminated immediate roof tends to detach from the main strata. Suspension theory assumes that the immediate roof of the excavation is weak whereas the upper layer is relatively stronger. In such situations, rockbolts hold the immediate roof to the self-supporting main roof via transmitting the dead weight load of the strata between face plates and anchors to the main roof. Figure 7 shows the weak roof strata suspended to the competent strata. It is required that the bolt should be long enough to anchor into the stable rock and that bolts should hold sufficient tensile strength to maintain the rock dead weight.

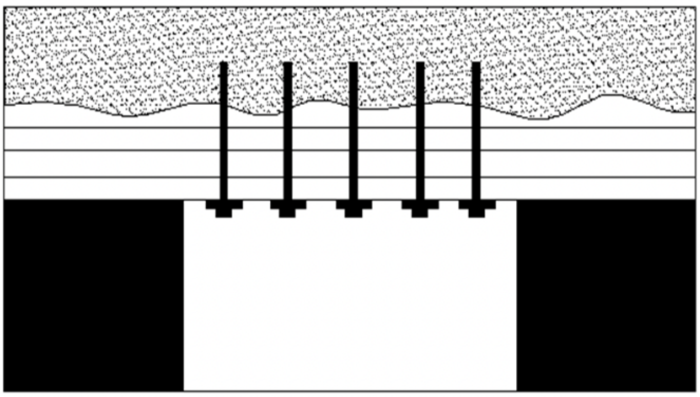

Figure 7. Suspension effect of roof bolting

These theoretical analyses illustrated a variety of potential rock stratum migration patterns under site-specific geological circumstances. In this case, the immediate roof strata are rather soft and are anticipated to collapse as the shield moves, hence a voussoir beam model is used to describe the movement of the lower strong roof strata(Figure 8). An overview of existing research related to this study

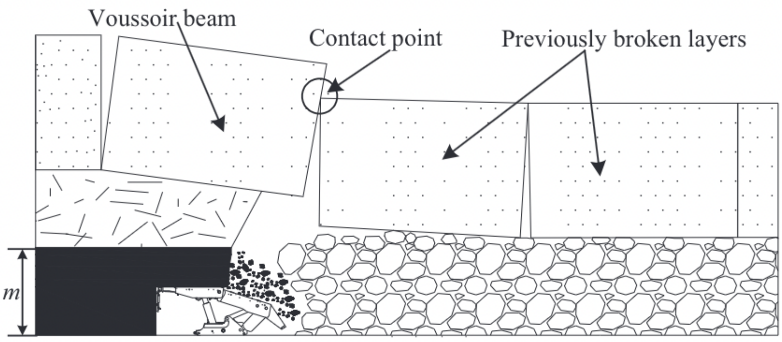

Figure 8. Voussoir beam model analyzed for thick roof

2.6 An overview of existing research related to this study

2.6.1 Numerical approach

According to (Gadde, Rusnak et al. 2008) no empirical guidelines exist which assist determine the proper bolt kind for a certain roof, as evidenced by earlier studies on roof stability. In reality, the goal of Peabody's Integrated Support Design Methodology is to achieve such an union (ISDM). The outcomes of this approach can give very precise information about how various roof bolt types perform when used on the same roof. (Fulawka, Stolecki et al. 2022) used c IIoT platform to contributes significantly to the creation of this experience by storing, reporting, and analyzing events. When every bolt is covered in sensors, the IIoT platform can be implemented successfully. This research paper can also serve as the foundation for the creation of a more thorough and accurate numerical model, which could have a favorable impact on the planning of underground excavation in difficult geological conditions and periodic geomechanical risk assessments. In research work of (Gao, Zagorščak et al. 2022) a coupled flow-geomechanical model is being used to study the ground deformation caused by geoenergy applications that demand complex thermohydraulic, chemical, and mechanically linked activities, such as underground coal gasification (UCG).

2.6.2 Field work, measurement, and instrumentation

The entry directed with in direction of the in-situ highest horizontal stress were in the optimum state, whereas those oriented at 90° was in the poorest, according to modeling results from (Gadde 2004).The intersections' highest and lowest levels of stability were observed at 0°/90°

and 45°, respectively. The greatest or worse situations, nevertheless, might also be observed at other orientations under specific input condition combinations. More research should be done on the effects of in-situ stresses on vast extraction regions because the majority of research papers focus on identifying the impact of horizontal stress on retreat workings (Hanna 1991)and (Brady and Brown 2006) research materials indicated that the beam and plate theories are commonly applied to the roof of entries and intersections, respectively. The previous studies of (Mark 2006) and (Molinda 2008) humidity in mines also play key role in foor stability. Based on these studies the importance of moisture sensitivity to ground control in weak roof was proved. This paper (Wang 2021) explains the ceiling collapse of a coal mine that took place on August 14, 2021, in Qinghai Province, China, resulting in 20 fatalities and 1 injured. This report covered the primary investigation of the tragedy, a brief account of the rescue efforts, and potential causes of the disaster. The two main causes of this occurrence are the fissure water and the damaged rock mass.

2.6.3 Empirical approaches

The empirical approach in engineering refers to a methodology that involves using observations, experiments, and data analysis to develop or improve engineering designs, processes, or systems. This approach is based on the principle that the best way to understand how something works or how to solve a problem is to gather empirical evidence through experimentation and observation. Engineers use this evidence to develop and test hypotheses, validate models, and refine their designs or processes. The empirical approach involves a cyclical process of observation, experimentation, and analysis, in which engineers gather data, analyze it, draw conclusions, and then use those conclusions to refine their designs or processes. This process is iterative, meaning that it is repeated until the desired results are achieved.

To quantitatively determine the rock conditions surrounding the tunnel, a new methodology built on the Rough Set (RS) theory and Rock Engineering Systems (RES) is developed (Adoko 2016). The risks of rock collapse from recent tunnel construction projects in China's Fujian province were examined. One method for evaluating the quantitative risk of rock collapse is the ground index (GI).One more related research paper was (Adoko 2017) GBI could be utilized to give engineers accurate quantitative data on the fall of the ground and the amount of hazard. The planned GBI was calculated using data from the Bamangwato Concession Limited (BCL), an underground mine in Selibe-Phikwe, Botswana. The Rock Engineering

Systems (RES) and Artificial Neural Network (ANN) techniques are used to construct the GBI. An extensive database on the features of the fall of ground (FoG) of the rock mass surrounding the excavation, which includes gravity-induced structurally regulated, block movement, and stress-induced failure events, was compiled. In research paper of (Brook, Hebblewhite et al. 2020) the roof characteristics of an underground coal mine located in the Bowen Basin, Queensland, Australia, have been illustrated using the coal mine roof rating (CMRR) and rock mass rating (RMR) description methodologies. Over a significant portion of the mine, both approaches have demonstrated consistency, despite differences in overall ratings in regions of difficult geology. In conclusion, this study demonstrates that the CMRR methodology is an effective method for describing the condition of the roof rock mass. The precise relationship between structural geology and rock mass categorization values, however, is still unclear. In the research of (Young, Walton et al. 2019) At U.S. Western Coal Mine A, the CMRR statistically correlates with the roof stability category, but not at Mine B. At any of the locations taken into consideration, the suitable ground stability category (1-4) could not be predicted with >70% accuracy using the CMRR alone. The factors being thought of right now don't completely explain roof stability at Mines A or B. Logistic regression research revealed that faulting, topographic curvature, and depth of cover had a decent capacity to predict the stability of the roof at Mine B. In (Bazarbay and Adoko 2021) research work also used an empirical approach as FIS to develop a knowledged-based system for assessing unplanned dilution in open stopes. One common thing for all research papers that mentioned above is that most of the classification made by empirical approaches are good, with accuracy more than 80%.This indicates that the empirical approach can be a more reliable tool for unplanned FoG assessment. Therefore, it is essential to create an expert system to see what kind of factors affects to FoG and prove by numerical simulation the stress at intersection sectors in tunnels. An expert system will also be used to assess the quality and strength of the rock mass surrounding a mine excavation. An expert system will determine by considering various factors such as the rock mass quality, the size and orientation of fractures, the presence of water zones, the rock stress conditions and geology. The rating system will range from 1 to 3, with higher ratings indicating greater stability of the rock mass.

Chapter 3. Fall of ground data description

3.1. Data source

The FoG data used in this thesis, were collect from the literature (Mueller 2010). According to the MSHA 7000 50a forms are thought to have the greatest collection of data on unintentional roof falls in the United States. Mine and Safety Health Administration (MSHA) coal oversight and enforcement is broken up into 11 Districts. This decision was made based on coal basins and unique ground control conditions in different parts of the country. This research based on 5 Districts, namely data was collected from 2-6 Coal Districts (Table 2).

Table 2.Districts and Coal Mines Name in USA

District and responsible geographical areas	Name of the mine
№2 Bituminous coal mining regions in Pennsylvania	TJS #5, Rossmoyne #1, Titus Mine, West Mine, Josephine #3, Tracy Lynne Deep, Logansport, Twin Rocks, Little Toby Mine, Dora 8, Ondo Extension, Ridge Deep, Madison Mine, Nolo Mine, Dooley Run Mine, Bailey Mine, Cherry Tree Mine, Quecreek #1, Genesis #17, Miller Mine;
№3 Maryland, Ohio, and Northern West Virginia	Whitetail, Tusky, Mountain View, Imperial, Blacksville No.2;
№4 Southern West Virginia	Round Bottom Powellton, Justice #1, Laurel Coalburg Tunnel Mine, No. 2 Gas, No. 130, Candice No. 2, Laurel Creek 5, Fork Creek Mine #1, Aracoma Alma, Ruby Energy, Cedar Grove Mine, Mountaineer II, No. 23 Mine, Lick Branch No. 2, Pocahontas Mine # 3, Midland Trail Mine #1, Copperhead #1, No. 1 and 5, Camp Springs, Josephine # 2, Poplar Ridge # 1, Pinnacle Mine, Rivers Edge, Upper Big Branch and etc.
№5 Virginia	Cherokee Mine, Roaring Fork No 4, Premium Mine, Dominion No 34, Honey branch, Deep Mine No 10, Deep Mine No 10 and etc.
№6 Eastern Kentucky	Meathouse Energy, Love Branch Mine, Simpson Branch, Advantage No 1, Clean Energy Mine, Raven Mine No 1, Van Lear Mine and etc.

Figure 9.Location of the 5 districts where FoG data was taken.

Fall of ground data was collected from 5 districts of the USA Coal Mines (Figure 9). In each district manages roughly from 3 to 20 underground mines. In total, 414 datasets about FoG. The primary criteria include elements that are known to affect FoG, such as support types, water content, and stratigraphic geology. Mainly the sample of data is given in Table 3.Some information like type of mining and geology of some districts was unavailable or missed, to fill this gaps I search it in the internet. Geology of 5 districts mainly was made of Claystone, siltstone, limestone, shale, and gray sandy shale. According on the ground conditions, supplements may be used in addition to the primary rockbolt (mechanically anchored, grouted, and tensioned) support systems. Initially given data was in ft, however as it is more convenient to make comparison in meters, all the data was converted from ft to meters. Microsoft Excel was used to analyze the taken data from the fall of ground investigation, and graphs were created to show the reported averages and distributions of fall dimensions. The full dataset is provided in Appendix .

Table 3.Sample of data

Seam	Geology	Support system	Water	FoG size		
				Length (m)	Width (m)	Height (m)
Upper Freeport	Brown, gray sandstone (12m thick) & gray sandstone (18m thick)	Tensioned rockbolt and cablebolts	No	36.6	5.8	2.4
Upper Freeport	Gray sandy shale & gray sandstone	Tensioned rockbolt	No	10.7	5.5	2.1
Sewickley	Gray shale (1.5m thick) & sandstone (6m thick)	Fully grouted rockbolt	No	7.6	5.2	1.9
Sewickley	Gray shale (4.5m thick) & sandstone(6m thick)	Fully grouted rockbolt	No	7.6	3.6	1.2
Sewickley	Gray shale (4.5m thick) & sandstone (6m thick)	Fully grouted rockbolt	No	9.15	4.9	1.5
Lower Kittanning	Dark laminated shale (1.2m thick) & gray sandy shale (4.8m thick)	Tensioned rockbolt	Yes	12.2	6.1	2.5
Lower Kittanning	Dark shale & gray shale (7.6m thick)	Fully grouted rockbolt	Yes	12.2	6.1	2.1
Lower Kittanning	Hard shale (14.3m thick) & sandstone (7.6m thick)	Fully grouted rockbolt	Yes	7.6	6.1	1.8

3.2 Description of the parameters

3.2.1 Geology

A combustible sedimentary rock called coal is made of old vegetation that has been compressed between other rock strata and changed over a long period of time by pressure, heat, and microbial action. This process is frequently referred to as "coalification." Coal is found in layers or seams with thicknesses varying from a few millimeters to several tens of meters. It consists mostly of carbon (50–98% of its total mass), hydrogen (3–13% of its total mass), and oxygen, with traces of nitrogen, sulphur, and other elements. Water and other inorganic material particles are also present. Coal burns to provide heat energy, which has several applications. The roof conditions can also be affected by the presence of water and high horizontal stresses, in addition to the particular geology in that area. The types of deposits immediately above coal can range from massive thick layers of sandstone or limestone, to strong laminated layers of siltstone and sandstone, to thin weak layers of shale or mudstone (Ávila and Figueiredo 2016). One of the most frequently seen overlying strata in coal mines is a laminated shale roof that is prone to immediate skin failure. In many mines, it is necessary to bolt wire mesh to the roof to prevent flaking and progressive failure of the weak shale layer, due in part to weathering and lateral confinement. The two main types of coal are brown and black, which have differing thermal qualities and applications. Mainly in this 5 types of districts geology consist of Gray sandyshale, gray sandstone, claystone, siltstone, limestone, shale. Based on this rock qualities were made approximate classification of layers according to their mineral's hardness. In table 4, illustrated the composition of rock and predicted hardness according to Mohs Hardness Scale.

Table 4.Input rock strata values (Mueller 2010)

Rock type	Young's Modulus (MPa)	Poisson's Ratio	Tensile Strength (MPa)	Friction Angle	Cohesion (MPa)
Limestone	5171.07	0.20	4.826	25	19.994
Poor Shale	689.48	0.30	1.034	25	1.999
Weak Limestone	2757.90	0.20	4.826	25	11.996
Grey Shale	2413.166	0.25	1.378	30	4.502
Black Shale	1378.952	0.25	1.378	30	3.302
Coal	1034.214	0.28	0.689	26	0.599
Claystone	310.2642	0.32	0.344	20	1.999
Shale	1378.952	0.3	1.034	25	1.999
Sandstone	3102.642	0.2	5.515	25	11.996

3.2.2 Fall of ground size

A fall of ground in a mine is an accident that occurs when a portion of the roof or walls of an underground mine collapses or falls. This can be caused by various factors, including geological instability, poor mine design, or inadequate support systems. The consequences of a fall of ground can be severe, including injury or death to mine workers, damage to equipment, and disruption of operations. Therefore, it is important for mining companies to take measures to prevent such accidents from occurring. One way to prevent falls of ground is to conduct regular geological assessments and to implement appropriate support systems in areas of the mine that are at risk of collapse. This can involve installing roof bolts, rock bolts, mesh, and other forms of reinforcement to provide additional support to the mine walls and roof. FoG is defined as the unintentional falling of loose rocks from excavation faces (roofs and side walls). In many geological and operational situations, FoG occurs in underground mines. Even with primary and secondary support structures in situ, the surrounding rock mass around mine entrances is prone to several kinds of collapse. These include rock collapses, cave-ins, raveling, squeezing, slabbing, bursting, etc. from the roof and the sides/ribs of apertures that can be structural or stress-induced, which poses risks to the industry (Adoko 2017). FoG size depends on length, width and height of fall in meters (Table 5).

An analysis shows that the maximum mining width, in the given data is from 5.54 meters to 6.66 meters, and the frequency is 230 times (Figure 10).

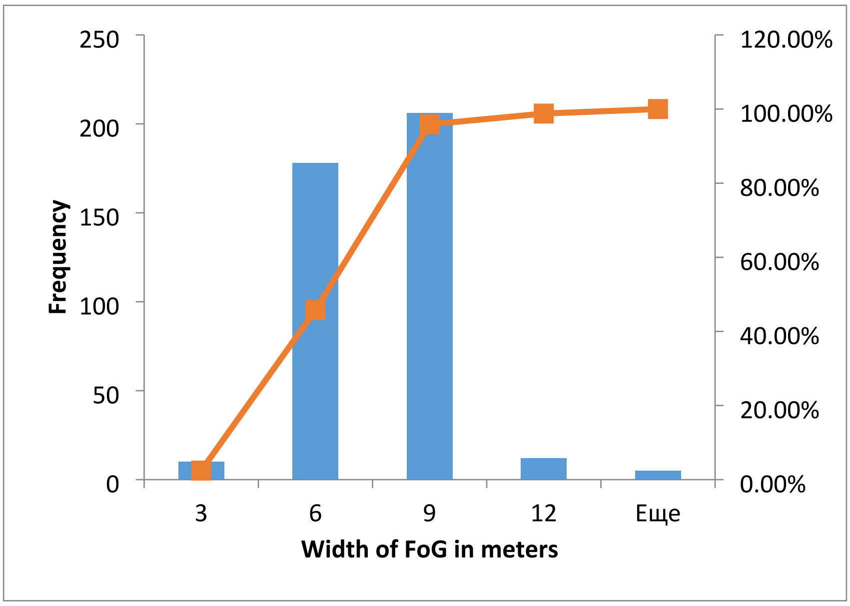

Figure 10. The FoG width distribution in underground mine

There was a quite unclear distribution of FoG height among given data, varying firstly relates to geographic location of the mine. To illustrate, the average extraction rate in Eastern mines is smaller than in Colorado. From figure 11. It is observed that most of mines have height from 3.05 meters to 12.35 meters.

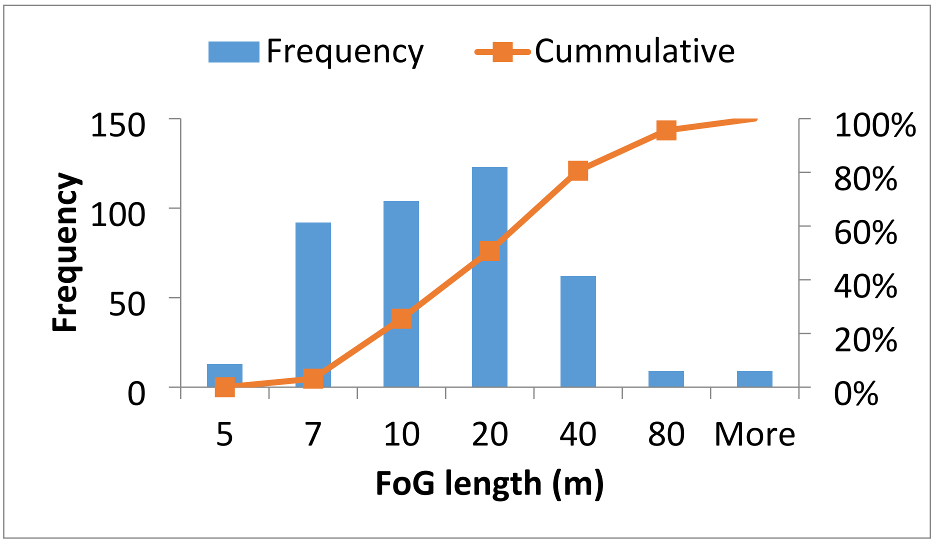

Figure 11.The FoG height distribution in underground mine.

By the given data and analyzes, it could be mention that the highest FoG size had district number 4 and the lowest one at district 3.

Table 5. FoG size range per districts

District	Max. FoG size/m3	Min. FoG size/m3
2	3398.00	25.80
3	1471.00	9.06
4	1886.30	16.90
5	645.62	21.00
6	637.00	25.00

3.2.3 Support system

As the coal mines subjected to roof failure, consequently, roof supports are used to stabilize the roof. They interact with the ground to create a stable rock structure. C. Mark suggests that regardless of the type of bolt used (mechanical, grouted, tensioned) the local geology has the largest role in determining which mode the bolt system is required for support. The intensity of support provided by a bolt system is determined by load bearing capacity of individual bolts, density of the bolting pattern, and the length of bolts (Mark, Molinda et al. 2005). The bolt grade and stiffness, as well as the anchoring mechanism could also be considered as factors within support intensity. Two frequently used bolt types in the U.S. are mechanical anchor and fully resin grouted bolts.

Tensioned bolts, also known as rock bolts or rock anchors, are commonly used in the mining industry to provide additional support to underground mine structures and to prevent rock mass failure. These bolts are typically made of high-strength steel and are installed into the surrounding rock using specialized drilling equipment. Tensioned bolts work by transferring the weight and stress of the overlying rock to the surrounding rock mass. The bolt is tensioned using a specialized hydraulic jack, which places the bolt under a controlled amount of tension. The tension in the bolt helps to hold the rock mass together and prevent it from collapsing or moving.

Fully grouted bolts, also known as fully encapsulated bolts or fully cement-grouted bolts, are a type of rock bolt commonly used in underground mining operations. These bolts are designed to provide additional support to the rock mass by bonding the surrounding rock to the bolt and creating a stable mass. Fully grouted bolts consist of a steel bolt that is inserted into a hole drilled into the rock. The bolt is surrounded by a cementitious grout, which is injected into the hole under pressure to fill the voids between the bolt and the rock. The grout sets and hardens, forming a bond between the bolt and the rock mass. The grout used for fully grouted bolts is typically a cement-based mixture that may also contain additives to improve its strength and bonding characteristics. The grout is usually pumped into the hole using a specialized injection pump and nozzle. Fully grouted bolts are often used in areas of the mine where the rock mass is weak or fractured and requires additional support. They are also useful in areas where ground movements or deformation are expected.

The 74% of all mines used fully grouted bolts for support system. Roughly three times smaller was used tensioned bolts 24%, and other percentages accounts for other support system like T-bar, anchors and etc. (Figure 12)

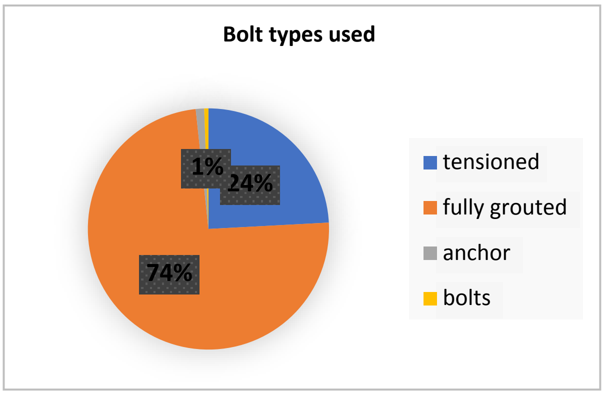

Figure 12.Bolt types used

A significant portion of the mines reported that they used different diameter bolts for different applications. Consequently, figure 14 was constructed based on data of bolt length from all 414 cases at underground mines accidents. The most common bolt was 1.8-1.98 m length (Figure 14). It is mostly depending on different seam height, and as analyses shows on layer which is above the coal seam. To illustrate, case number 32 (Table 6) the bolt length is 1,82m, because it used to install it on the rock type 2- sandstone, because it is harder than rock type 2-shale. The thickness of shale layer is 1,525m, so the bolt length is longer than shale layer.

Table 6. Fall of ground data on case 15

rock type 1	rock type 2	thickness 1	thickness 2	Bolt type	Bolt length in meters	Water	Length	Width	Height	volume of FoG/m
Shale	Sandstone	1,53	3,66	Fully grouted	1,82	No	10,06	27,43	2,74	756,91

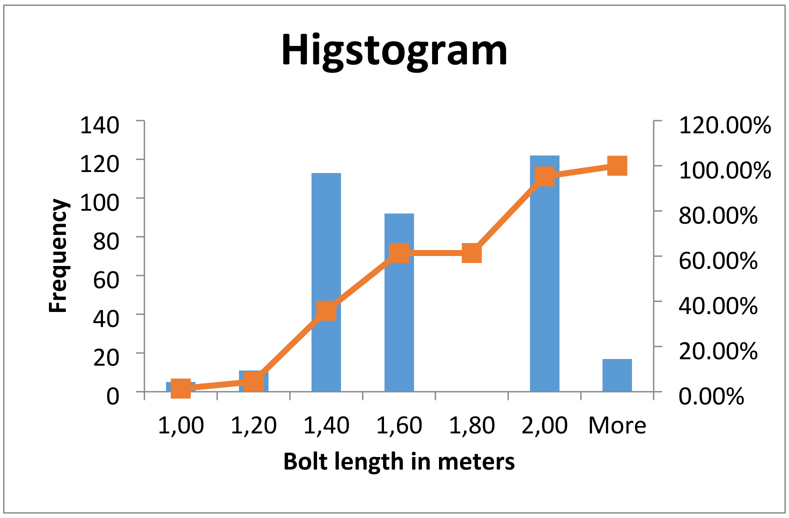

Figure 13. Bolt length distribution

3.3 Basic statistics analyses

The 7000 50a reports' data were gathered, and different histograms was used to analyze them. The independent factors that influenced the fall of ground data's length, width, height, and volume were identified using statistical analysis of variance test (Table 7). The MSHA District, bolt type (active/passive), bolt length, immediate roof thickness, and the existence of water or cutters close to the fall were all considered separate factors. It is significant to note that each site's geology is one of the most crucial elements in the likelihood and severity of roof falls. Due of the large variation between mines, statistical analysis may or may not derive meaningful findings.

Table 7.Statistical description of parameters

	Length of FoG	Width of FoG	Height of FoG	Volume of FoG
Average	15.90	5.85	2.40	239.76
Min	3.05	1.22	0.60	0
Max	188	19.50	24.38	3550.93
Standard Deviation	10.13	0.77	0.73	189.18
Variation	387.13	2.37	2.06	155362.9

Chapter 4. Numerical simulation of FoG in tunnel intersection at local mines

Introduction to the chapter:

In this chapter, I present the result of the simulations of the tunnel intersections under various scenarios. The goal of this chapter was to simulate different cases and understand how the support system, type of rock and presence of water affect to stress and displacement in underground mine. The chapter organized as follows: first the model set up is explained, then the simulations results are presented followed by discussions of the results.

4.1 Model set up

In this thesis a 2D problem is assumed, even if stress around tunnel is a 3D problem. However, by considering a plan strain situation we made a decision to simulate the excavation in underground and to see from above what will happen.

RS2 from Rocscience is a software suite that provides advanced numerical modeling and simulation capabilities for geotechnical engineering applications. This software has been successfully used in previous similar research (Mueller 2010) due too many advantages. Here are some potential advantages of:

1. Comprehensive Functionality: provides a comprehensive set of tools and functions for geotechnical analysis and design, it has complex simulations and modeling of geotechnical systems and structures.
2. User-Friendly Interface: RS2 has a user-friendly interface that allows users to quickly and easily set up and run simulations.
3. High Accuracy: RS2 is based on advanced numerical methods that are designed to provide high accuracy in geotechnical analysis and design.
4. Customizable: RS 2 is highly customizable, with the ability to create user-defined material models, boundary conditions, and analysis procedures.
5. Integration: RS 2 can be easily integrated with other software tools and platforms, including CAD and GIS software, to provide a comprehensive solution for geotechnical analysis and design.

Overall, RS 2 provides a comprehensive, user-friendly, and accurate solution for geotechnical analysis and design. Its advanced numerical methods, customizability, and integration capabilities make it a valuable tool for geotechnical engineers and researchers.

The related sizes in RS2 for our project is 20 in each side (0,0; 20,0; 20,20; 0,20) because it I domain, but the maximum length of FoG could be more than 80m. The thickness of coal layer at all simulations were 2m and the length is 6m. The bottom layers is not playing a key role, as the unplanned fall of ground mostly goes by roof. The rock properties were taken from Table 8.

Table 8. Input rock parameters

Rock type	Young's Modulus (MPa)	Poisson's Ratio	Tensile Strength (MPa)	Friction Angle	Cohesion (MPa)
Limestone	5171.07	0.20	4.82	25	19.99
Poor Shale	689.48	0.30	1.03	25	1.99
Weak Limestone	2757.90	0.20	4.82	25	11.99
Grey Shale	2413.16	0.25	1.37	30	4.50
Black Shale	1378.95	0.25	1.37	30	3.30
Coal	1034.21	0.28	0.68	26	0.59
Claystone	310.26	0.32	0.34	20	1.99
Shale	1378.95	0.3	1.03	25	1.99
Sandstone	3102.64	0.2	5.51	25	11.99

The material properties were taken from Table 8 and inserted to the window of material properties in RS2 (Figure14), mainly it was properties like Poisson's ratio, Young's modulus, tensile strength, friction angle and cohesion.

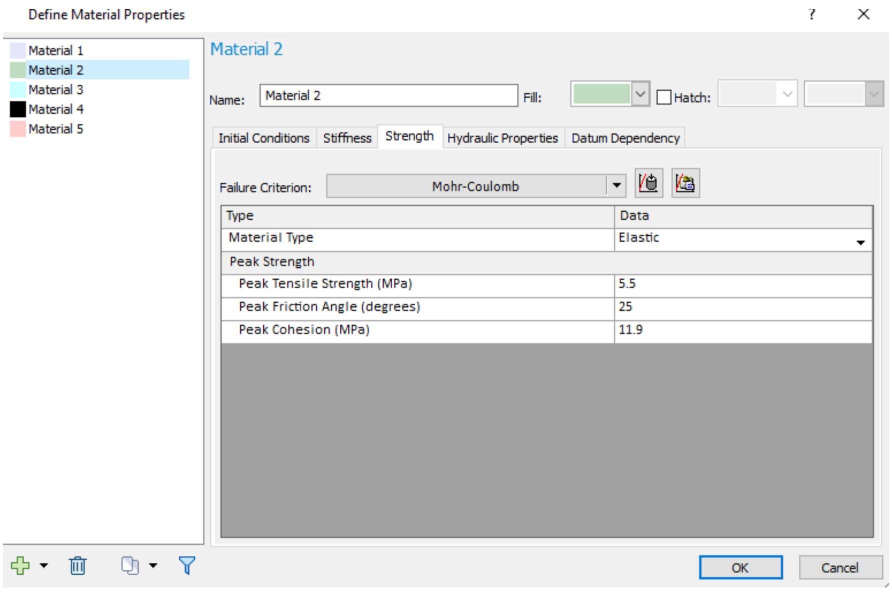

Figure 14. Input material parameters window

4.2 Simulation of displacement at intersection points of excavation.

In previous research the simulation was made from the cross-section view (reference). Which is in fact incorrect, the main reason for that is he did not considered stress at intersection points

(Table 9). Consequently, to prove that the stress at intersection point of coal mine is higher, the simulations were carried out based on 15th FoG case highlighted in Figure 19,20. The entire FoG cases are provided in Appendix 1.

Table 9.Fall of ground data on case 15

Seam	rock type 1	rock type 2	thickness 1	thickness 2	Bolt type	Bolt length in meters	Supplemental	Water	Length	Width	Height	volume of FoG/m
Sewickley	shale	sandstone	1,37	3,66	Fully grouted	1,83	3,6m cables	No	5,18	3,05	3,05	48,14

The thickness of the first layer is 3.66m and it is sandstone, all the properties was taken from Table 8. The next layer is 1,375 m and it is shale, after 2m layer of coal and there made 6m length excavation, the bottom rock types is not given in the dataset. To provide more stability for roof, engineers used fully grouted bolts and cables as supplements (Figure 15). The length of bolts is longer than the thickness of shale layer. On figure 15, they illustrated as red fully grouted bolts, so they installed to harder and more competent rock – sandstone. Also, as additional support system used supplements – cables. These cables' principal benefit is their ability to be put in apertures with very little headroom. The cables can either be tensioned before grouting or grouted in situ without tensioning. The mesh is uniform.

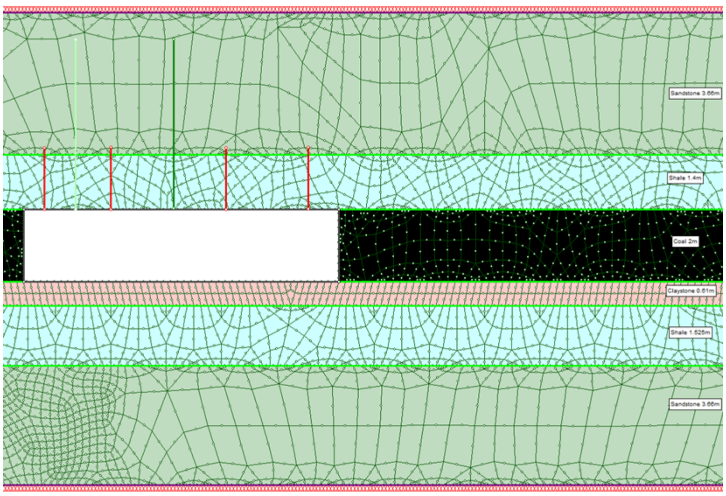

Figure 15.Illustration of 15th case lithology

In previous research works simulation was mainly made the same as in Figure 17, which is in fact incorrect. Because this piece of cut shows the stress relise as minor at intersection point, to show that the stress is high in the intersection of excavation and rock, we created a cross-section cut from the above as in Figure 18. This simulation shows that where the plane

AB and CD cross has the highest indicator of displacement, not at the endings of excavations. To show this tunnel intersections we used joints at the both end of excavations, to simulate cross cuts as in Figure 16.

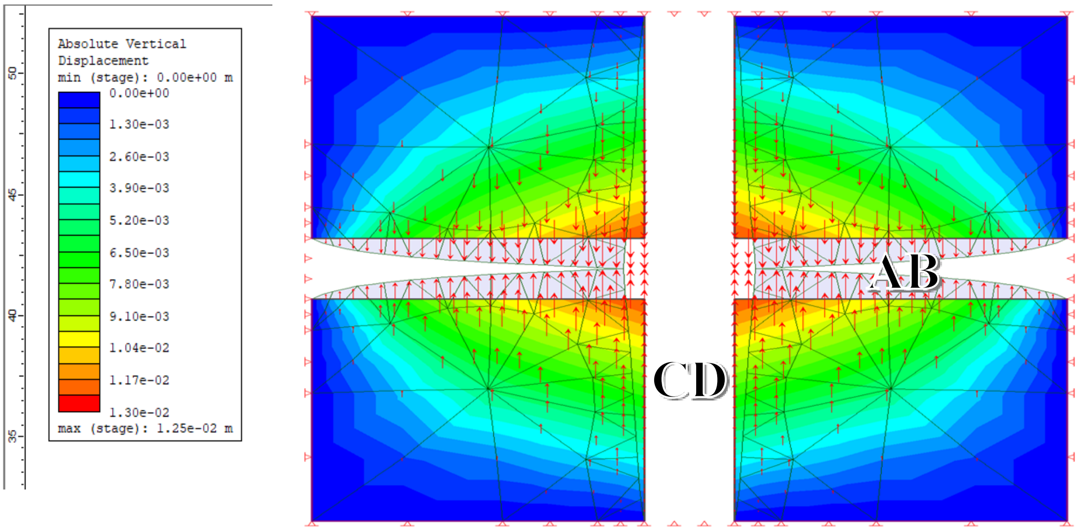

Figure 16.Simulation of the case from the above

So, if we compare figure 17 and figure 18 we see that stress and the points X,Y,Z,P is become higher, than on figure 18.

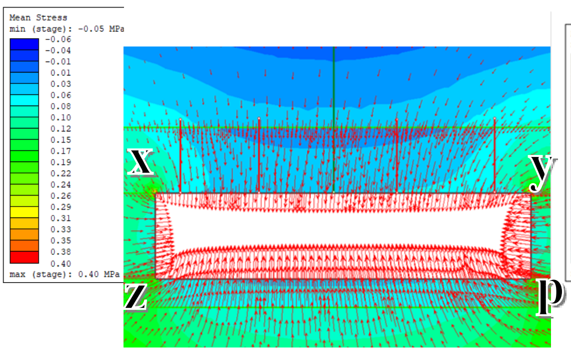

Figure 17.Simulation of the case #15

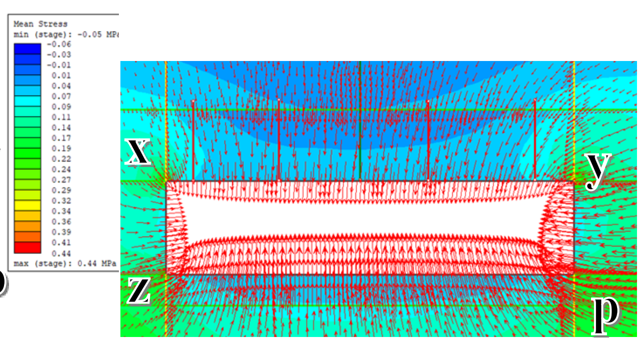

Figure 18. Simulation of the case #15 with intersections

In conclusion, by the above simulations we can make conclusion that the FoG is more likely happen at intersection points of excavation, rather than along length or width of excavation.

4.3 Simulation of maximum, medium and minimum volume of FoG

Three cases of FoG (Table 10) was simulated to see the relationship between field data and simulation results based on geology (input rock parameters), support type(bolt type and length) and presence of water. The case 187 is minimum FoG, the medium is 40th case and the maximum case number is 42.

Table 10. Parameters of 3 cases

rock type 1	rock type 2	Thickness 1	Thickness 2	Bolt type	Bolt length in meters	Supplemental	Water	Length	Width	Height	volume of FoG/m
Hard shale	Gray sandstone	7,32	8,54	Fully grouted	1,83	Cables	No	5,18	0,00	-	0,00

rock type 1	rock type 2	Thickness 1	Thickness 2	Bolt type	Bolt length in meters	Water	Length	Width	Height	volume of FoG/m
Shale	Sandy shale	5,80	6,71	Fully grouted	3,66	Yes	182,88	5,79	3,35	3550,93

rock type 1	rock type 2	Thickness 1	Thickness 2	Bolt type	Bolt length in meters	Water	Length	Width	Height	volume of FoG/m
Shale	Sandstone	1,22	6,10	Fully grouted	1,21	No	8,22	6,70	4,26	235,48

Total displacement at figure 19 shows the smallest amount of displacement, because the indicator of FoG size is 0, but the width is 1.5 which is very small and means that unplanned fall of ground happened along width of excavation. Maximum total displacement is 1.02e-03 and small red area on the top shows there maximum amount of displacement which could happen. Moreover, the density of arrows is not so big as on next Figures 21,22.

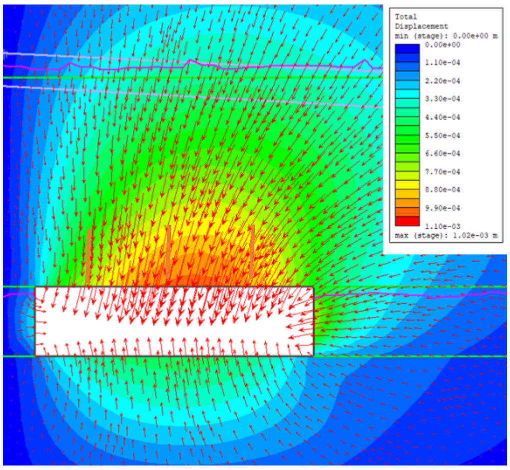

Figure 19. Simulation of small FoG case

Total displacement in figure 21 shows the highest amount of displacement, because the indicator of FoG size is 3350. Maximum total displacement is 1.51e-03 and long red area on the top shows there maximum amount of displacement which could happen. Moreover, the arrows of displacement move from roof and bottom side of excavation crossing each other, consequently it can hardly be denied that the occurrence of unplanned roof falls high.

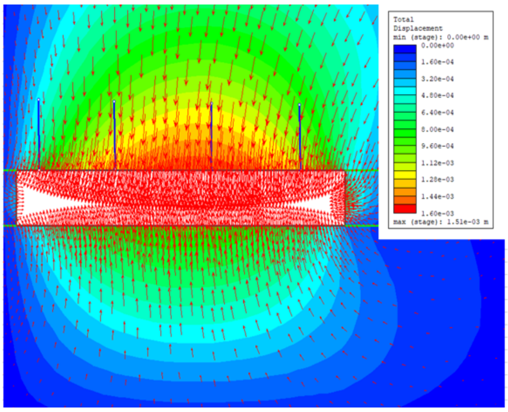

Figure 20.Simulation of high FoG case

Total displacement at figure 22 shows the medium amount of displacement, because the indicator of FoG size is 235(see Table 10). Maximum total displacement is 5.37e-04 and long red area on the top shows there amount of displacement which could happen. Moreover, the arrows of displacement even cannot reach the center of excavation which means that the displacement is miserable.

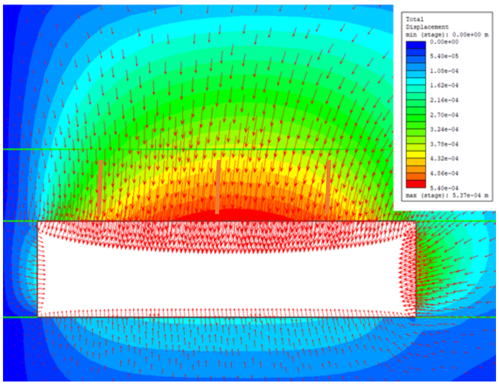

Figure 21. Simulation of medium FoG case

The next three pictures illustrates the amount of mean stress ,mainly overburden stress at three cases-minimum, medium and maximum FoG cases related to field observations. On figure 22 shows result of simulation with mean stress indicator in case of low FoG. As you see, stress is mainly around the excavation, but not at upper side, it is likely to happen because of support systems used. Moreover, one thing that should be noted is that presence of water has minor affect on FoG. At the top of excavation has minor stress, which unlikely to cause FoG. So it could be concluded that even if the ground consist of weak rock, the installed support system can turn it to competent ground.

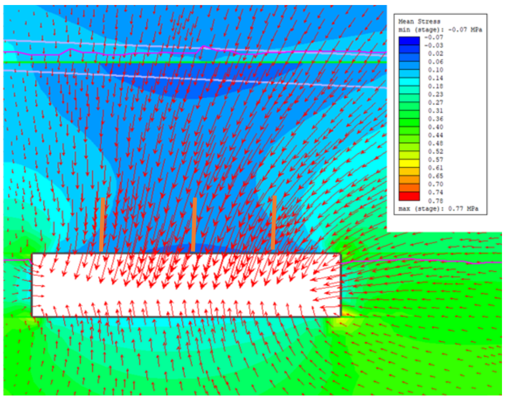

Figure 22. Result of simulation with mean stress indicator in case of low FoG

On figure 23 shows result of simulation with mean stress indicator in case of high FoG. Stress is mainly around the excavation, but not at upper side, it is likely to happen because of support systems used. Moreover, one thing that should be noted is that the highest stress mentioned at corner intersection points of excavation.

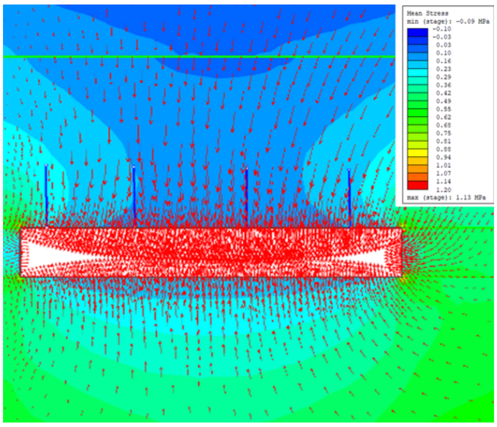

Figure 23.Result of simulation with mean stress indicator in case of high FoG

On figure 24 shows result of simulation with mean stress indicator in case of medium FoG. Stress is mainly around the excavation, also medium overburden stress can be noticed at corners of intersections. Moreover, one thing that should be noted is that the highest stress mentioned at corner intersection points of excavation.

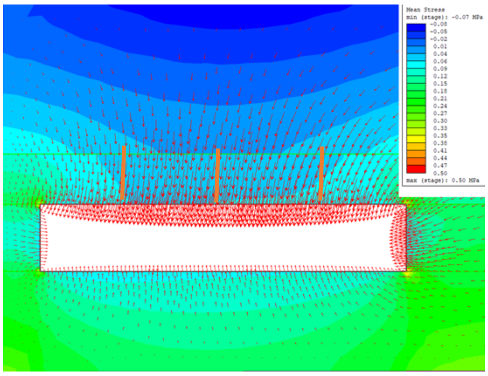

Figure 24. Result of simulation with mean stress indicator in case of medium FoG

4.4 Discussion of numerical simulation results:

Overall, on figure 23 we have high density of displacement arrows, but on Figures 22 and 24, a smaller density of arrows (showing field stress, displacements) can be seen. which serves as prove for small displacement, so there is good agreement between field data and simulation results. In Figure 23, the displacement of roof and bottom arrows are already crossing each other, which is indicator of high overburden stress. It can be concluded that presence of water do not influence on simulation results of displacement and stress. However, the bolt length and presence of support system highly affect to stress and displacement.

Chapter 5. Establishing a FIS for FoG at tunnel intersections

Introduction to the chapter:

Unplanned roof falls in an excavation intersections are frequently linked to fatalities, accidents, and financial losses; as a result, they constitute a severe danger to the profitability of coal mines and the life of working stuff in underground. Despite ground control technology advancements, fall of ground (FoG) at tunnel intersections happens frequently. The design of coal mine development excavations invariably uses subjective data and knowledge, which results in unintended ground instability. These factors are not considered by traditional design tools. The goal of this chapter is to provide expert systems that can accurately assess the connection between unexpected roof falls, support techniques, and geology. The chapter organized as follow: first an overview of FIS, second modelling of an expert system and the last one validation .

5.1 An overview of Fuzzy Inference System (FIS)

FIS is a form of approximate reasoning, in which the notion of fuzzy set introduced by (Zadeh 1965), plays a fundamental role. FIS stands for Fuzzy Inference System, which is a type of artificial intelligence system that uses fuzzy logic to handle uncertain and imprecise information. FIS is a powerful tool for modeling complex systems, especially those that involve human expertise or natural language.

Here are some expert-knowledge areas related to FIS:

1.Fuzzy Logic: Fuzzy logic is a mathematical framework that allows for reasoning with uncertain and imprecise information. FIS use fuzzy logic to model complex systems by creating rules that link input variables to output variables.

2.Membership Functions: Membership functions are used to define how input variables relate to output variables. These functions describe the degree of membership of an input variable to a fuzzy set. Membership functions are used to create fuzzy rules that map input variables to output variables.

3.Rule Base: The rule base is a set of rules that defines how input variables are mapped to output variables. Fuzzy rules are typically written in the form "if-then" statements. The rule base is a crucial component of the FIS, as it defines how the system will behave under different conditions.

4.Defuzzification: Defuzzification is the process of converting fuzzy output variables into crisp output variables. This process is necessary because most real-world systems require crisp, quantitative output variables.
5.FIS Applications: FIS can be applied in many different fields, including control systems, pattern recognition, data analysis, and decision-making. FIS is especially useful in situations where there is uncertainty or ambiguity in the input data.
Overall, FIS is a powerful tool for modeling complex systems that involve uncertain or imprecise information. It has many applications in various fields and can be used to solve a wide range of problems. Without exact quantitative analysis, FIS can simply simulate the qualitative features of language human knowledge and reasoning processes. (Yu, Guo et al. 2005). Takagi-Sugeno and Mamdani Methods are the two most popular and well-known FIS methodologies (Takagi and Sugeno 1985) (Mamdani and Assilian 1975)Although the Sugeno fuzzy inference system is not intuitively sensitive, it has been more frequently chosen over the Mamdani method in real estate valuation practices (Kuşan, Aytekin et al. 2010) due to Mamdani's complexity, which requires expert knowledge in the selection of membership and rule bases. For the Sugeno inference system, the numbers of input, output, and subset are crucial since an increase in the numbers needs a longer training period and results in a more complicated structure for Sugeno to be used for real estate appraisal. While Mamdani uses expert knowledge to enable the system to forecast output for various input values, it does so in accordance with the data set. Because the available data are frequently uncertain, it is crucial in the real estate market to forecast real estate values in line with human intuition, where Mamdani is promising (Sygnowski, Trawinski et al. 2008) (Mert and Yilmaz 2009). The distinctive feature of a fuzzy set is that it is a set without a crisp whose elements possess partial degree of membership with values ranging from 0 to 1. It is a convenient tool to represent gradual and partial membership to a set which are often encountered in rock engineering system. For example, the FoG variables' spaces can be considered as a fuzzy set. FIS defines any form of relationships between input and output variables of a system by employing a series of linguistic descriptions in a sense of a fuzzy set (i.e., FoG is high) defined by membership functions, logical operations and IF-THEN rules which is refereed as fuzzy inference process. This process of mapping from a given input to an output using fuzzy logic provides the basis from which decisions can be made or patterns discerned. In the inference process of the fuzzy rule, the fuzzy proposition needs to be represented by an implication function. Basically, there are two ways of generating a FIS: expert knowledge-based approach and data-driven methods.

A general structure of a FIS is illustrated in Figure 25. Some example of research related to geomechnics in which FIS were used include: An evolutionary adaptive neuro-fuzzy inference system for estimating field penetration index of tunnel boring machine in rock mass (Adoko and Yagiz 2019); model for fuzzy inference system for online social network analysis (Ramalingam and Baskaran 2017); unplanned dilution prediction (Bazarbay and Adoko 2021)

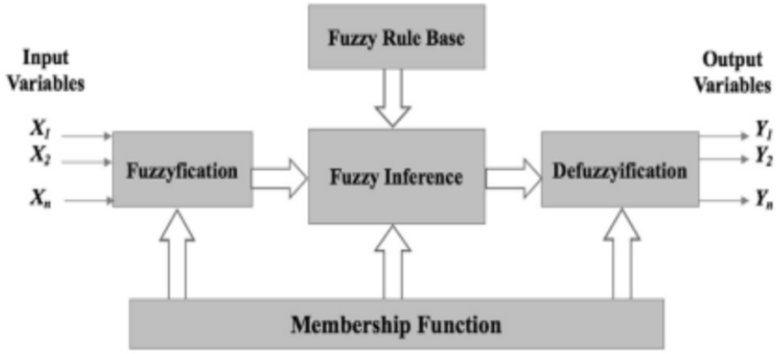

Figure 25. General structure of a FIS (martínez-barrera, Gencel et al. 2017)

5.2 FIS modelling

The FIS was built using a technique based on expert knowledge. This technique was chosen due to its flexibility. Data-driven FIS could be used but since we do not have enough quantitative data in terms of input parameters, this option was discarded. The FIS model inputs were the geology of the strata (P1), the types of support (P2), and the presence of groundwater or no (P3) while the model output was the FoG size. In order to translate qualitative attributes into the FIS, it was important to encode them into numeric (categorical) in a scale of 1-3 or 0-1 on basis of the ground conditions. For example, for a ground composed by limestone and claystone lithology is rated 3; if supported with fully grouted rockbolt and supplements, the support rating is 3 and with presence of water, the corresponding rating is 1. The FoG size, on the other hand was rated based on the frequencies as detailed in Table 11. This resulted in obtaining 51%, 30% and 19% of minor, moderate, and major FoG cases, respectively.

Table 11. Parameter description and rating

Parameters	Description of the ground condition					
	Poor ground conditions	Rating	Fair ground conditions	Rating	Competent ground conditions	Rating
Lithology (dominant)	Mostly shale (sandy shale, shale, laminated shale, dark shale, grey	3	Shale together with claystone, siltstone, siltstone	2	Sandstone, limestone,	1

	shale, slickensided shale)					
Support type	Tensioned bolts	3	Fully grouted and supplements	2	No support	1
Presence of water	Yes	1	No/yes	N/A	No	0
FOG size (length)	Major (>20 m)		Moderate (10-20 m)		Minor (<10 m)	

The construction of the FIS starts with specifying the type of FIS to build. Here, the Mandani type is selected. In the command window of Matlab, the fuzzy designer is invoked; the system has 3 input variables and one output. To each variable, 3 membership's functions were added except for input variable water. This allowed to divide the variable spaces into 3: low (L), moderate (M), and high (H) for lithology, support type and FoG; while two categories L and H were used for thepresence/absence of water. The parameter space was rated according to Table 8. To match the variable spaces, bell- shaped membership functions were used for their flexibility. Examples of the membership associated with the parameters are shown in Figs. (27-30). In total, 18 rules(i.e. 3^2x2^1) were required to implement the FIS model mechanism. Hence, I used my personal opinion and knowledge to build the fuzzy rules. Figure 26 shows the architecture of the FIS. A sample of the rules is provided as follows:

1. If (P1 is Low) and (P2 is Low) and (P3 is Low) then (FoG is High)
2. If (P1 is Low) and (P2 is Low) and (P3 is High) then (FoG is High)
3. If (P1 is Low) and (P2 is Moderate) and (P3 is High) then (FoG is High)
4. If (P1 is Low) and (P2 is Moderate) and (P3 is Low) then (FoG is Moderate)
5. If (P1 is Low) and (P2 is High) and (P3 is Low) then (FoG is Low)
6. If (P1 is Low) and (P2 is High) and (P3 is High) then (FoG is Moderate)
7. If (P1 is Moderate) and (P2 is Low) and (P3 is Low) then (FoG is Moderate)
8. If (P1 is Moderate) and (P2 is Low) and (P3 is High) then (FoG is Low)
9. If (P1 is Moderate) and (P2 is Moderate) and (P3 is Low) then (FoG is Low)

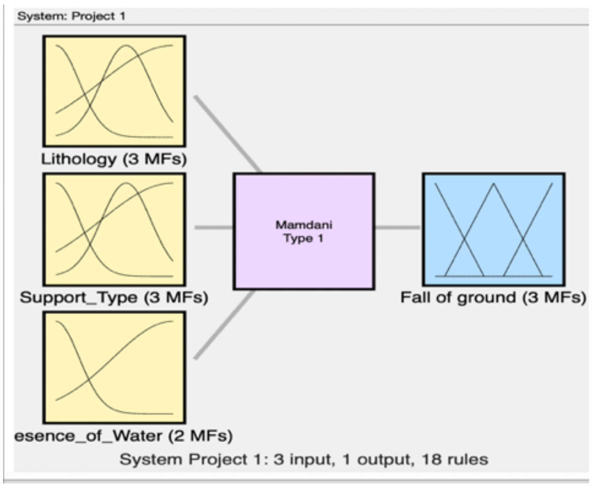

Figure 26. FIS architecture

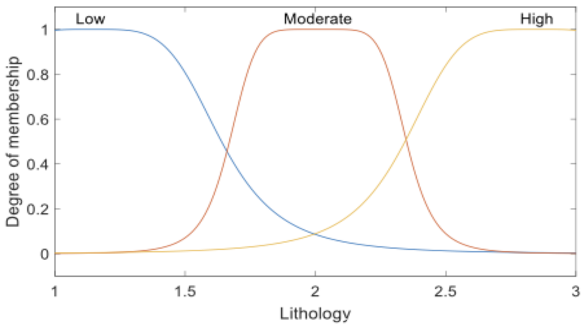

Figure 27. Membership functions for lithology

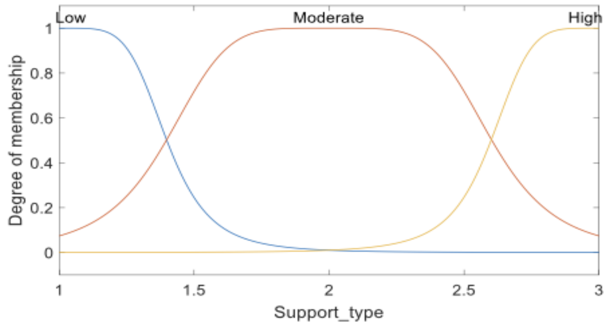

Figure 28. Membership functions for support type

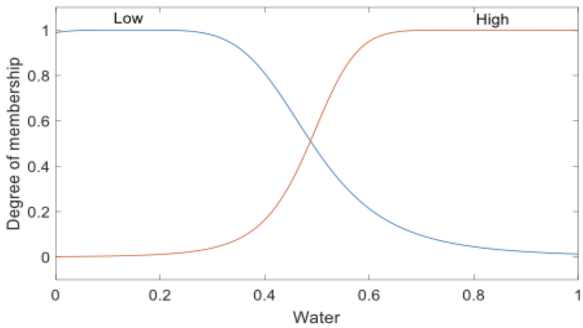

Figure 29. Membership functions for presence of water

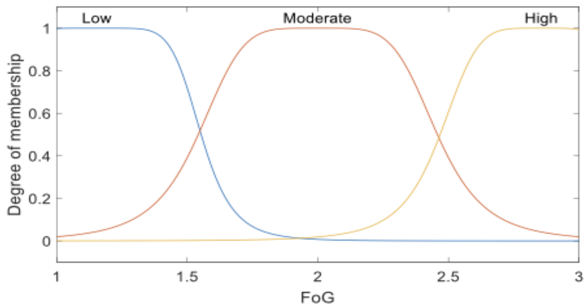

Figure 30.Membership functions for FoG size

Fig. 31 illustrates a graphical representation of the system. For example, when lithology is 1, support type is 1 and water is 1 then FoG is 2.02 (which corresponds to moderate FoG). The

FIS was evaluated using the dataset with the help of "*EVALFIS*" function in MATLAB. Table 12 provides some results.

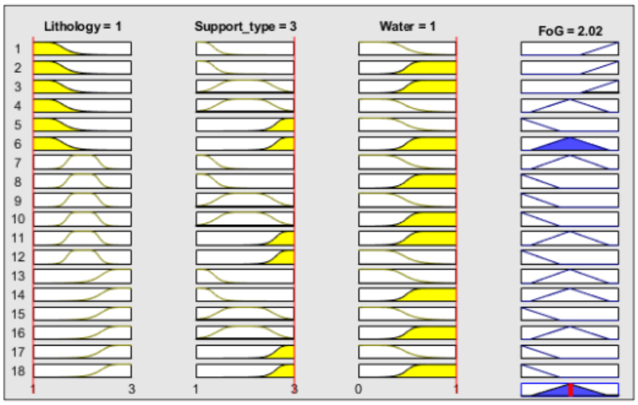

Figure 31. Graphical representation of the FIS

Table 12 Evaluation sample

P1	P2	P3	Actual FoG	FIS output	Predicted FoG	P1	P2	P3	Actual FoG	FIS output	Predicted FoG
2	3	0	3	2.92	3	2	2	0	1	1.44	1
1	3	0	1	1.42	1	2	2	0	2	1.54	2
3	3	0	2	1.42	1	2	3	0	1	1.42	1
2	3	0	1	1.42	1	3	2	0	3	2.9	3
2	3	0	1	1.42	1	2	3	0	1	1.42	1
2	3	0	2	1.65	2	1	3	0	2	1.42	1
2	2	0	2	1.46	1	2	2	1	3	2.6	3
2	2	0	1	1.44	1	2	2	1	1	1.5	1 or 2
3	2	1	1	1.5	1 or 2	2	3	0	1	1.42	1
2	2	1	1	1.5	1 or 2	1	2	0	2	2	2
2	2	0	1	1.44	1	2	3	0	1	1.42	1
3	2	0	1	1.44	1	2	3	0	1	1.42	1
3	3	0	2	1.74	2	3	1	0	2	2.7	3

5.3 Validation

In order to validate the results, the FIS model is considered as a classification problem and the classification performances were evaluated using the accuracy, sensitivity (true positive rate), and specificity (false positive rate). These metrics represent an indication of the classification quality and are determined using Eqs. 6-8 as follows:

$$\text{Accuracy}=\frac{T_p + T_n}{T_p + T_n + F_p + F_n} \quad (6)$$

$$\text{Sensitivity}=\frac{T_p}{T_p + F_n} \quad (7)$$

$$\text{Specificity}=\frac{T_n}{T_n + F_p} \quad (8)$$

In Eqs. 6-8, F_p, T_p, F_n and T_n represent: false positive, true positive, false negative, and true negative, respectively.

Table 13.Confusion matrix

Actual FoG	Predicted FoG			
	Minor	Moderate	Major	Percent. correct
Minor	155	30	24	74 %
Moderate	22	83	18	67 %
Major	6	10	64	80 %

Table 14. Performance summary

	Accuracy	Sensitivity	Specificity
Minor FoG	0.80	0.74	0.86
Moderate FoG	0.81	0.67	0.86
Major FoG	0.86	0.80	0.87
Average	0.82	0.74	0.87

A sample of the predicted FoG is provided in Table 12. The confusion matrix of the classification is shown in Table 13. As it can be seen, moderate FoG sizes were the most misclassified (40 out of 123 were misclassified) which corresponds to a correct classification rate of 67%. The best performance corresponds to major FoG (80% of success rate). The average computed accuracy, sensitivity and specificity values for the employed dataset were of 82%, 74% and 87%, respectively (Table 14). These results are good enough to reflect the correlations between the unplanned FoG and its influencing factors. The overall performances showed good predictability of the FIS.

5.4 Discussions

Overall, the results indicated quite good agreement with the field observations. The correct classification rate varied between 67 and 80%. This suggests that the fuzzy rules were adequate enough. For example, "If (P1 is Low) and (P2 is Low) and (P3 is Low) then (FoG is High)". This makes more sense. So instead of using equations to quantify FoG, these rules can be used. From the rules, it can also be seen that water doesn't affect the FIS outcomes.

Chapter 6. Conclusions

6.1 Summary of the main results

Numerical modelling was conducted in Chapter 4. RS2 was used to simulate to see the displacement at intersections of excavation and how the field data and simulations coincides. The main results are summarized as follows:

- Numerical modelling showed good agreement with the field data. The field data with maximum, medium and minimum simulations showed the same results. In highest and smallest FoG data the stress and displacement was matching.
- Large FoGs are likely to happen in tunnel intersection more often compare to non intersection.
- Length of FoG affects to the size of FoG, so the length of FoG directly proportional to size of FoG. Which means that unplanned fall of ground usually occurs along length of excavation
- Support length prevent underground mines from FoG and the length of support play key role, if it is long and installed to strong layer, the overburden layer of excavation will be more competent, rather than short bolt which installed to weak layers.
- Presence of water do not affect to FoG, in simulation process not influenced on displacement or stress in underground excavations.

FIS was conducted in chapter 5. MATLAB was used to create an expert system which is capable to identify how different conditions affect to FoG. The main results are summarized as follows:

- Knowledge-based expert system showed good agreement with field data. The correct classification rate varied between 67 and 80%.
- Large FoG is likely to happen where the roof rocks are weak and do not have support system.
- Presence of water miserably affect to FIS outcomes.

6.2 Research limitations

Firstly, it is worth mentioning that there was some elements which were difficult to simulate in Chapter 4. For example,the presence of water in simulation showed minimum affect because the depth or the way water goes was unknown for us. Secondly, at simulating intersection points in RS2 was only one plain X,Y, however if we can use Z plane we could more clearly show stress at intersection points. It is not considering the exact length of excavation, intersection coordinates, the rock which is below excavation.

The FIS study has also limitations. There were subjectivities involved in defining and rating the FoG size and its parameters. Also, incorporating more parameters (e.g. tunnel span and full rock mass characterization), could lead to better FIS performance. It is worth mentioning that the results indicated that P3 has limited influence on the results. This can be interpreted by the fact the employed FoG dataset contains only few cases with presence of water. The present FIS can be refined by adopting 5 membership functions. In this case, it would be preferable to adopt a data-driven approach to generate the FIS rules to avoid constructing manually a large amount of fuzzy rules. Despite these limitations above mentioned, the current results could serve as a basis for further studies.

6.3 Conclusions and recommendations

This thesis examined the literature to gain a better understanding of the present state of fall of ground in coal mine intersection sectors. Numerous methodologies and approaches generated to access and predict FoG in underground coal mine intersection sectors, each with its own set of advantages and downsides, which discussed in this work. One of the merits of this present study, is that the results can provide a mean to numerically simulate the FoG and analyze it's influencing factors. This fundamental aspect was not considered in previous studies (Mueller, 2010). The numerical simulation of FoG based on data showed that the stress at intersection points has more stress and more likely to have displacement, rather than along at any point of length or width of excavation. For further research it is recommended to include to FIS expert system other input parameters like mining type, RMR of rocks, seam thickness and etc. For RS2 simulations it is recommended to simulate this occasions at 3D and try to use precise coal and excavation parameters.

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Appendix

Seam	Geology				Support system			Water	Fall size in meters			
	rock type 1	rock type 2	thickness 1	thickness 2	**Bolt type**	**Bolt length in meters**	**Supplements**		**Length**	**Width**	**Height**	volume
Upper Freeport	Brown gray sandstone	gray sandstone	12,192-18,288	12,192-18,288	tensioned	1,83	1,5x2,4m cables	Yes	36,58	5,79	2,44	516,50
Upper Freeport	Gray sandyshale	gray sandstone	1,83		tensioned	1,22	1,8m tens	No	10,67	5,49	2,13	124,88
Upper Freeport	Gray sandyshale	gray sandstone			Fully grouted	1,52	3mcables		13,72	6,10	3,66	305,82
Upper Freeport	dark shale	gray sandy shale	2,75	1,83	Fully grouted	1,2192 and 1,8288		No	12,19	5,18	2,13	134,79
Sewickley	gray shale	sandstone	1,53	6,10	Fully grouted	1,83	2,7m tens	No	7,62	5,18	1,98	78,23
Sewickley	gray shale,	sandstone	4,58	6,10	Fully grouted	1,22		No	7,62	3,66	1,22	33,98
Sewickley	gray shale	sandstone	4,58	6,10	Fully grouted	1,22		No	9,14	4,88	1,52	67,96
Sewickley	shale	sandstone	1,53	3,66	Fully grouted	1,83		No	5,18	5,18	3,05	81,84
Sewickley	shale	sandstone/sandy siltstone	1,53	4,58	Fully grouted	1,524	Fully grouted	No	9,14	6,10	3,66	203,88
Sewickley	shale	sandstone	1,37	3,66	Fully grouted	1,83	3,6m cables	No	5,18	3,05	3,05	48,14
Sewickley	shale	sandstone			Fully grouted	1,22	3,6m cables	No	22,86	4,88	3,66	407,76
Sewickley	shale	sandstone/sandy siltstone	1,53	4,58	Fully grouted T-bar	1,52		No	12,50	3,05	2,44	92,88

Sewickley	shale	shale or sandstone	1,53	4,58	Fully groutedT-bar	1,83		No	9,75	5,49	3,96	212,04
Lower Kittanning	slickensided shale	sandstone	1,53	6,10	Fully grouted	1,22		No	10,06	9,45	2,74	260,71
Lower Kittanning	gray shale	gray sandstone	7,32	8,54	Fully grouted	1,2192 and 1,8288		Yes	9,14	6,10	2,74	152,91
Lower Kittanning	gray shale,	gray shale/sands tone	7,32	8,54	Fully grouted	1,22		Yes	12,19	5,49	3,66	244,66
Lower Kittanning	slickensided shale	sandy shale	6,10	13,12	Fully grouted	0,91		No	7,92	4,57	1,52	55,22
Lower Kittanning	gray shale	sandy shale	6,10	13,12	Fully grouted	0,9144		No	7,92	4,57	1,52	55,22
Lower Kittanning	dark laminated shale	gray sandy shale	1,22	4,88	Fully grouted	1,07	Spot cables & longer bolts	No	18,29	5,79	1,37	145,27
Lower Kittanning	laminated dark shale	gray sandy shale	1,22	4,88	Fully grouted posts	1,07		No	12,19	5,49	1,22	81,55
Lower Kittanning	dark shale	gray sandy shale	8,24	4,88	Fully grouted	0,9144		No	7,62	4,88	1,22	45,31
Lower Freeport	gray shale,	grayshale/s andy shale	3,66	6,41	Fully grouted	1,07		No	9,14	5,79	1,83	96,84
Lower Freeport	gray shale,	gray sandy shale	3,66	3,05	supertwists,F ully grouted, tensioned	1,8288 and 1,524	1,8X3m cable	No	30,48	5,49	3,05	509,70
Lower Freeport	gray shale	sandy shale	3,66	9,76	T-bar		2,4-3,66m cables	No	5,79	1,83	2,44	25,82
Lower Freeport	gray shale with sandstone streaks	gray shale	3,66	4,58	Fully grouted	1,07		No	60,96	6,10	2,44	906,14
Lower Freeport	gray shale,	sandy shale	3,66	6,10	Fully grouted	1,83	spot 3,66m cables	No	7,62	6,10	2,13	99,11

Lower Freeport	gray shale	sandy shale	3,66	6,10	Fully grouted	1,2192 and 1,8288	3,66m & 4,27m cables	No	27,43	6,10	4,27	713,58
Lower Freeport	gray shale	sandy shale	3,66	6,10	Fully grouted	1,2192 and 1,8288		No	36,58	6,10	3,05	679,60
Lower Kittanning	Dark gray shale	grayshale		7,63	Fully grouted	1,0668 and 1,8288		Yes	12,19	6,10	2,13	158,57
Lower Kittanning	hard shale,	hardshale	14,34	7,63	Fully grouted	1,22		Yes	7,62	6,10	1,83	84,95
Lower Kittanning	hard shale	silty hard shale	14,34	76,25	Fully grouted	0,91		No	7,62	4,57	1,83	63,71
Lower Kittanning	shale	sandstone	0,46	4,58	Fully grouted	1,83	3,66m cables	No	7,62	5,49	4,57	191,14
Pittsburgh	dark shale	sandstone	6,10	4,58	Tensioned	1,83		No	6,10	6,10	4,57	169,90
Upper Freeport	dark shale/	shale	0,61	3,05	Fully grouted	1,22		No	27,43	6,10	1,83	305,82
Upper Freeport	shale	mud shale	1,22	6,10	Fully grouted	1,2192 and 1,524	beams and props	No	8,23	6,71	4,27	235,48
Upper Freeport	shale,	shale	6,10	6,10	Fully grouted	1,22	beams and props	No	6,71	6,10	3,66	149,51
Lower Kittanning	shale	sandy shale/sands tone	5,80	6,71				no	182,88	5,79	3,35	3550,93
Lower Kittanning	shale,	sandy shale/sands tone	5,80	6,71	Fully grouted	1,98	3m cables, 2,4m spacing	No	19,81	9,14	3,35	607,40
Lower Kittanning	shale	shale	6,10	6,10	double tens T-bar	2,13	3m cables, 2,4m spacing		18,29	5,49	2,13	214,08
Lower Kittanning	dark shale	sandy shale	9,15	6,71	point anchor	1,52		No	16,76	5,49	2,44	224,27

Lower Kittanning	dark shale	sandy shale	9,15	6,71	Fully grouted	1,83	1,5m x3,66m cables	No	6,10	6,10	3,05	113,27
Lower Kittanning	dark shale	sandy shale	9,15	6,71	point tens	1,83	3,66m cables	No	18,29	6,10	24,38	2718,42
Lower Kittanning	dark shale,	shale with sandstone	9,15	6,71	Tensioned	1,83		No	9,14	6,10	2,44	135,92
Lower Kittanning	dark shale	shale with sandstone	9,15	6,71	Tensioned	1,83		No	12,19	6,10	2,44	181,23
Lower Kittanning	dark shale,	shale with sandstone	9,15	6,71	Tensioned	1,22		No	9,14	4,27	1,52	59,47
Lower Kittanning	laminated shale,	sandy shale	5,80	6,71	Tensioned	1,22		Yes	12,19	6,10	2,44	181,23
Lower Kittanning	laminated shale	sandy shale	5,80	6,71	Tensioned	1,52		No	10,67	6,10	2,13	138,75
Lower Kittanning	laminated shale	sandy shale	5,80	6,71	active	1,22		No	42,67	5,49	4,27	999,02
Lower Kittanning	dark soft shale,	shale with sandstone	9,15	6,71	active	1,22	3,66m cables	No	15,24	5,79	3,66	322,81
Sewickley	Drawslate	shale/sands tone			Fully grouted	1,22		No	12,19	12,19	6,10	906,14
Pittsburgh #8	gray shale	sandy shale	1,98	7,02	Fully grouted channels	2,44		No	16,15	4,88	3,96	312,16
Pittsburgh	laminated shale	sandstone	2,44	6,71	Tensioned	2,4384-3,6576		No	12,19	4,88	3,66	217,47
Pittsburgh	shale/coal,	shale	1,83	6,71	Tensioned	2,44		No	9,14	4,88	2,13	95,14
Pittsburgh	shale/coal	shale	1,98	6,71	TensionedT5 ch	2,44		No	9,14	4,88	2,13	95,14

Upper Freeport	sandy shale	shale or sandy shale	1,53	4,58	Fully grouted	1,83	3,66m cables	Yes	9,14	5,79	3,05	161,41
Upper Kittanning	shale	grey shale	3,05	6,10	Fully grouted	1,2192 and 1,8288	3m cables	No	121,92	6,10	4,57	3398,02
Upper Kittanning	shale	laminated shale	3,05	6,10	Fully grouted	1,2192 and 1,8288	3m cables	No	73,15	6,10	4,57	2038,81
Upper Kittanning	laminated shale	sandstone	1,53	4,58	Tensioned	1,52		No	12,19	6,10	2,13	158,57
Upper Freeport	shale	sandstone	2,44	3,05	Fully grouted	1,2192 and 1,524	2,4m cables	No	9,14	9,14	3,05	254,85
Upper Freeport	shale	sandstone	1,83	3,05	Fully grouted	1,22		No	14,33	6,10	1,83	159,71
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	Screen & trusses	No	7,62	5,49	2,44	101,94
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	Screen & 3,66m cables	No	6,10	5,49	2,44	81,55
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	Screen & 3,66m cables	No	6,10	5,18	2,13	67,39
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	Screen	No	24,38	5,18	2,13	269,58
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted pans	1,83	3,66m cables	No	6,10	6,10	2,44	90,61
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted pans	1,83	3,66m cables	No	6,10	6,10	2,44	90,61
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted pans	1,83	3,66m cables	No	6,10	6,10	2,44	90,61
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted pans	1,83	3,66m cables	No	6,10	6,10	2,44	90,61
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted pans	1,83	3,66m cables	No	6,10	6,10	2,44	90,61
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted pans	1,83	3,66m cables	No	6,10	6,10	2,44	90,61
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted pans	1,83	3,66m cables	No	6,10	6,10	2,44	90,61

Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83		No	18,29	5,49	2,44	244,66
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	3,66m cables	No	6,10	6,10	2,44	90,61
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	3,66m cables	No	6,10	6,10	2,44	90,61
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83		No	18,29	5,49	2,44	244,66
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	3,66m cables	No	6,10	6,10	2,44	90,61
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	3,66m cables	No	6,10	6,10	2,44	90,61
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	3,66m cables	No	9,14	5,49	2,44	122,33
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	3,66m cables & trusses	No	7,62	6,71	2,13	109,02
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	3,66m cables	No	7,62	5,18	2,13	84,24
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	Trusses	No	6,10	6,10	2,13	79,29
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	Trusses	No	6,10	5,18	2,44	77,02
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	Trusses	No	6,10	5,18	2,13	67,39
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	Trusses	No	3,05	2,44	1,22	9,06
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83		No	12,19	5,18	2,13	134,79
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	3,66m cables	No	7,62	7,62	2,44	141,58
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	3,66m cables & cribs	No	5,49	5,49	2,13	64,22
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	3,66m cables	No	9,14	5,18	2,13	101,09

Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	3,66m cables	No	10,67	5,18	3,66	202,18
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	Cables & screens	No	3,05	2,44	2,44	18,12
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	Cables	No	12,19	5,49	2,44	163,11
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted	1,83	& jacks	No	7,62	5,24	2,44	97,41
Lower Kittanning	sandy shale	claystone	3,81		Fully grouted straps	1,83	3,66m cables	No	9,14	5,24	2,13	102,29
Middle Kittanning	hard shale	gray sandstone	5,34	14,49	Fully grouted	1,22	Timber	No	24,38	5,49	4,57	611,64
Middle Kittanning	hard shale	gray sandstone	5,34	14,49	Fully grouted	1,22	Cables	No	6,10	6,10	1,83	67,96
Middle Kittanning	hard shale	gray sandstone	5,34	14,49	Fully grouted	1,22	3,66m cables	No	21,34	5,49	1,22	142,72
Middle Kittanning	hard shale	gray sandstone	5,34	14,49	Fully grouted	1,52	Cables	No	9,14	5,24	1,22	58,45
Upper Freeport	shale	siltstone	1,05		Tensioned	1,83	Roof mats	No	4,88	4,88	3,05	72,49
Upper Freeport	shale	siltstone	1,05		Tensioned	1,83	Screen	No	7,62	6,10	2,74	127,43
Upper Freeport	shale	siltstone	1,05		Tensioned	1,83	Screen	No	16,76	4,88	4,57	373,78
Upper Freeport	shale	siltstone	1,05		Tensioned	1,83	Screen	No	4,88	4,88	3,05	72,49
Upper Freeport	shale	siltstone	1,05		Tensioned	1,83	Screen	No	7,62	4,88	1,83	67,96
Upper Freeport	shale	siltstone	1,05		Tensioned	1,83	3,66m cables & trusses	No	7,62	6,10	2,74	127,43
Upper Freeport	shale	siltstone	1,05		Tensioned	1,83	Screen	No	4,27	3,66	1,83	28,54
Upper Freeport	shale	siltstone	1,05		Tensioned	1,83		No	6,10	4,88	1,83	54,37
Upper Freeport	shale	siltstone	1,05		Tensioned	1,83	3,66m spot bolts	No	6,10	4,88	3,96	117,80
Upper Freeport	shale	siltstone	1,05		Tensioned T5 ch	1,83	3,66m cables	No	6,10	5,49	3,66	122,33

Upper Freeport	shale	siltstone	1,05		Tensioned T5 ch	1,83	Screen	No	6,10	4,88	1,83	54,37
Upper Freeport	shale	siltstone	1,05		Tensioned T5 ch	1,83	Screen	No	7,62	4,88	1,83	67,96
Middle Kittanning	shale	sandstone	5,80	6,10	Fully grouted	1,83		No	5,24	4,57	1,98	47,49
Middle Kittanning	shale	sandy shale	5,80	6,10	Fully grouted	1,83		No	110,00	5,49	2,44	1471,58
Pittsburgh 8	shale	redstone/li mestone	4,27	5,34	Tensioned straps	2,44		No	12,19	4,88	2,44	144,98
Pittsburgh 8	shale	redstone/li mestone	4,27	5,34				No	3,66	3,05	2,44	27,18
Pittsburgh 8	shale	redstone/li mestone	4,27	5,34	Tensioned T3 ch	2,44	4,88m cables	No	9,14	3,66	3,05	101,94
Pittsburgh 8	shale	redstone/li mestone	4,27	5,34	Tensioned T3 ch	2,44	3,66m cables	No	3,05	2,13	3,66	23,79
Pittsburgh 8	shale	redstone/li mestone	4,27	5,34	Tensioned T3 ch	2,44		No	6,10	4,88	2,74	81,55
Pittsburgh 8	shale	redstone/li mestone	4,27	5,34	Tensioned T3 ch	2,44		No	10,67	4,88	3,05	158,57
Pittsburgh 8	shale	redstone/li mestone	4,27	5,34	Tensioned	2,44		No	4,27	3,05	2,44	31,71
Pittsburgh 8	shale	redstone/li mestone	4,27	5,34	Tensioned	2,44	3,66m cables	No	7,62	4,88	2,44	90,61
Pittsburgh 8	shale	redstone/li mestone	4,27	5,34	Tensioned	2,44		Yes	4,88	2,74	2,44	32,62
Pitt sburgh 8	shale	redstone/li mestone	4,27	5,34	Tensioned	2,44		Yes	21,64	4,88	2,44	257,34
Powellton	sandy shale	grey shale	3,81					No	21,34	6,10	2,44	317,15
	sandy shale	grey shale	3,81					No	18,29	6,10	2,13	237,86
	sandy shale	grey shale	3,81					No	13,72	6,10	3,05	254,85
	sandy shale	grey shale	3,81					No	6,10	6,10	1,83	67,96
	sandy shale	grey shale	3,81					No	12,80	5,79	3,96	293,76

	sandy shale	grey shale	3,81					No	24,38	5,49	3,66	489,32
	sandy shale	grey shale	3,81					No	15,24	5,49	4,88	407,76
	sandy shale	grey shale	3,81					No	18,29	5,49	3,66	366,99
	sandy shale	grey shale	3,81					No	9,14	6,10	2,44	135,92
	sandy shale	grey shale	3,81					No	9,14	6,10	1,52	84,95
	sandy shale	grey shale	3,81					No	9,14	6,10	1,52	84,95
	sandy shale	grey shale	3,81					No	6,10	5,79	1,52	53,80
	sandy shale	grey shale	3,81					No	6,10	6,10	1,83	67,96
	sandy shale	grey shale	3,81					No	91,44	6,10	3,66	2038,81
#2 Gas	shale	sandy shale	1,53	4,58				No	30,48	5,79	2,13	376,61
	shale	sandy shale	1,53	4,58				No	30,48	5,49	2,13	356,79
	shale	sandy shale	1,53	4,58				No	30,48	2,74	1,83	152,91
	shale	sandy shale	1,53	4,58				No	18,29	5,79	2,44	258,25
2 Gas	shale	sandy shale	1,53	4,58	Fully grouted	1,52		No	9,14	7,62	2,44	169,90
	shale	sandy shale	1,53	4,58	Fully grouted	1,22		No	21,34	6,10	1,83	237,86
Alma & Cedar Grove	shale	sandy shale	1,53	4,58				No	6,10	5,79	2,74	96,84
	shale	sandy shale	1,53	4,58	Fully grouted	1,22		No	7,62	6,10	1,37	63,71
	shale	sandy shale	1,53	4,58				No	18,29	6,10	1,98	220,87
	shale	sandy shale	1,53	4,58	Fully grouted	1,22		No	9,14	5,49	1,37	68,81
	shale	sandy shale	1,53	4,58				No	9,14	6,10	1,83	101,94
	shale	sandy shale	1,53					No	9,14	9,14	1,22	101,94
	shale	sandy shale	1,53		Fully grouted	1,22		No	15,24	6,10	1,83	169,90

	shale	sandy shale	1,53					No	21,34	6,10	2,44	317,15
Beckley	hard shale	claystone	3,81					No	12,19	6,10	1,83	135,92
Beckley	hard shale	claystone	3,81		Fully grouted	1,22		No	6,10	6,10	1,52	56,63
Beckley	hard shale	claystone	3,81		Tensioned	1,83		No	6,10	3,66	1,83	40,78
Beckley	hard shale	claystone	3,81		fully grouted	1,22		No	12,19	6,10	1,52	113,27
Beckley	hard shale	claystone	3,81		fully grouted	1,52		No	6,10	6,10	1,52	56,63
Beckley	hard shale	claystone	3,81		tensioned	1,2192 and 1,524		No	6,10	6,10	1,83	67,96
Beckley	hard shale	claystone	3,81		tensioned	1,83		No	5,49	4,88	2,13	57,09
Beckley	hard shale	claystone	3,81		tensioned	1,2192 and 1,524		No	12,19	6,10	1,52	113,27
Beckley	hard shale	claystone	3,81		tensioned	1,2192 and 1,524		No	21,34	6,10	1,52	198,22
Beckley	hard shale	claystone	3,81		tensioned	1,83		No	6,10	6,10	2,44	90,61
Beckley	hard shale	claystone	3,81		tensioned	1,2192 and 1,524		No	12,19	6,10	1,52	113,27
	hard shale	claystone	3,81					No	10,67	5,49	1,07	62,44
Coalburg	hard shale	gray sandstone	7,32	8,54	Bolts		Cribs	No	9,14	6,10	3,05	169,90
Coalburg	hard shale	gray sandstone	7,32	8,54	fully grouted	1,22	Cribs	No	6,10	3,05	0,91	16,99
	hard shale	gray sandstone	7,32	8,54	fully grouted	1,22		No	10,67	5,79	1,22	75,32
Winifred	hard shale	gray sandstone	7,32	8,54	Tensioned	1,52		No	18,29	6,10	1,83	203,88
Pocahontas 2	hard shale	gray sandstone	7,32	8,54	fully grouted	1,22		Yes	6,10	4,57	1,52	42,48
Pocahontas 2	hard shale	gray sandstone	7,32	8,54				Yes	24,38	6,10	1,52	226,53

Pocahontas 2	hard shale	gray sandstone	7,32	8,54	fully grouted	1,22		Yes	33,53	6,10	1,52	311,49
Pocahontas 2	hard shale	gray sandstone	7,32	8,54	fully grouted	1,22		Yes	60,96	6,10	1,52	566,34
Lower Kittanning	hard shale	gray sandstone	7,32	8,54	Tensioned	1,52		No	9,14	5,49	2,13	107,04
Pocahontas 3	hard shale	gray sandstone	7,32	8,54	tensioned	1,52		No	9,14	5,49	3,66	183,49
Pocahontas 3	hard shale	gray sandstone	7,32	8,54	Fully grouted	1,52		No	188,00	5,49	1,83	1886,30
Powellton	hard shale	gray sandstone	7,32	8,54	fully grouted	1,52		No	6,10	5,79	2,44	86,08
Powellton	hard shale	gray sandstone	7,32	8,54	Fully grouted	1,52		No	6,10	6,10	2,44	90,61
Eagle	hard shale	gray sandstone	7,32	8,54	tensioned	1,22		No	6,10	6,10	1,52	56,63
Eagle	hard shale	gray sandstone	7,32	8,54	tensioned	1,22		No	6,10	6,10	1,37	50,97
Eagle	hard shale	gray sandstone	7,32	8,54	tensioned	1,22		No	6,10	6,10	1,37	50,97
Eagle	hard shale	gray sandstone	7,32	8,54	Fully grouted	1,22		No	30,48	5,49	1,22	203,88
Eagle	hard shale	gray sandstone	7,32	8,54	Fully grouted	1,22		No	18,29	5,49	1,52	152,91
Eagle	hard shale	gray sandstone	7,32	8,54	Tensioned	1,22		No	9,14	6,10	1,37	76,46
	hard shale	gray sandstone	7,32	8,54				No	15,24	6,10	1,83	169,90
	hard shale	gray sandstone	7,32	8,54	tensioned	1,52		No	73,15		2,44	0,00
	hard shale	gray sandstone	7,32	8,54	tensioned	1,52		No	30,48	6,10	2,13	396,44
Eagle	hard shale	gray sandstone	7,32	8,54	Fully grouted	1,22		No	115,82	5,79	1,52	1022,24

	hard shale	gray sandstone	7,32	8,54	Fully grouted	1,22		No	7,62	6,10	1,98	92,03
	hard shale	gray sandstone	7,32	8,54	Fully grouted	1,22		No	12,19	6,10	1,52	113,27
	hard shale	gray sandstone	7,32	8,54	tensioned	1,83		No	6,10	6,10	2,13	79,29
	hard shale	gray sandstone	7,32	8,54	Tensioned	1,83		No	12,19	6,10	1,98	147,25
	hard shale	gray sandstone	7,32	8,54	Tensioned	1,52		No	6,10	6,10	1,52	56,63
	hard shale	gray sandstone	7,32	8,54	Fully grouted	1,52		No	5,79	5,79	1,52	51,11
Peerless	sandy shale		3,81		Fully grouted	1,22		No	15,24	6,10	1,52	141,58
	sandy shale		3,81		fully grouted straps	1,52		No	23,16	5,49	2,13	271,16
Fire Creek	sandy shale		3,81					No	6,10	6,10	1,83	67,96
	sandy shale		3,81		Tensioned and points	1,8288 and 2,4384		No	9,14	6,10	3,05	169,90
	sandy shale		3,81		Fully grouted	1,52	Cables	No	32,00	5,49	2,44	428,15
	sandy shale		3,81		Fully grouted	1,52	Cables	No	32,00	5,49	2,44	428,15
	sandy shale		3,81		Fully grouted	1,22		No	6,71	6,10	1,83	74,76
	sandy shale		3,81		Fully grouted			No	15,24	6,10	1,83	169,90
	sandy shale		3,81		Fully grouted	1,22		No	21,34	6,10	1,52	198,22
Powellton	sandy shale		3,81		Fully grouted spot	1,8288 and 1,2192		No	6,10	6,10	4,57	169,90
Powellton	sandy shale		3,81		Fully grouted spot	1,8288 and 1,2192		No	6,10	6,10	4,57	169,90
	sandy shale		3,81		Tensioned	1,52		No	18,29	5,49	1,83	183,49
Sewell	sandy shale		1,58		fully grouted			No	15,24	5,49	1,22	101,94
Coalburg	sandy shale		1,58		fully grouted	1,52		Yes	30,48	6,10	3,05	566,34

Coalburg	sandy shale		1,58		fully grouted	1,52		Yes	30,48	6,10	2,13	396,44
	sandy shale		1,58		fully grouted	1,22		No	9,14	6,10	1,22	67,96
	sandy shale		1,58		fully grouted	1,22		No	8,53	6,71	1,37	78,49
	sandy shale		1,58		fully grouted	1,22		No	10,67	5,79	1,52	94,15
Upper Powellton	sandy shale		1,31		fully grouted	1,22		Yes	21,34	6,10	1,83	237,86
	sandy shale		1,31		fully grouted	1,52		No	12,19	6,10	2,74	203,88
					Tensioned	1,52		No	9,14	6,10	2,44	135,92
Douglas Red Ash					fully grouted			No	9,14	6,10	1,22	67,96
Alma					point	1,52		No	30,48	5,49	3,66	611,64
					Tensioned	1,52		No	9,14	6,10	1,83	101,94
					Tensioned	1,83		No	35,05	6,10	2,44	521,03
Alma					Tensioned	1,83	2,4m cables	No	121,92	6,10	3,05	2265,35
						1,22		No	30,48	5,49	1,83	305,82
					fully grouted	1,22	Cribs	No	18,29	6,10	1,83	203,88
					Tensioned	1,83		No	18,29	5,79	2,13	225,97
Cedar Grove					Fully grouted	1,52		No	3,05	3,05	2,44	22,65
					Fully grouted	1,22		No	6,10	6,10	3,05	113,27
					Fully grouted	1,22		No	11,58	5,49	1,22	77,47
					fully grouted	1,22		No	10,67	9,14	1,52	148,66
					tensioned	1,83		No	12,19	5,64	2,13	146,68
					tensioned	1,52		No	13,72	6,10	1,83	152,91
					tensioned	1,83		No	6,10	6,10	2,44	90,61

					Fully grouted	1,2192 and 1,8288		No	10,67	5,79	1,52	94,15
					Tensioned	1,52		No	7,62	6,10	2,44	113,27
					tensioned T5 straps	1,83	2,4m cables	No	9,14	6,10	2,44	135,92
					Fully grouted	1,22		No	7,62	6,10	1,22	56,63
					Fully grouted	1,52		No	9,14	7,62	1,22	84,95
								No	9,14	4,88	1,83	81,55
					Fully grouted	1,52		No	15,24	6,10	2,13	198,22
Williamson					Fully grouted	1,52		No	7,32	6,10	3,05	135,92
					Fully grouted	1,2192 and 1,8288		No	30,48	6,10	1,83	339,80
Pocahontas No. 3					tensioned	1,52		No	18,29	6,10	1,83	203,88
#2 Gas					tensioned	1,83	3,6m cables	No	15,24	6,10	2,44	226,53
Pocahontas No. 3								No				0,00
Sewell					Fully grouted	1,22		No	15,85	6,10	1,68	161,97
Eagle					Fully grouted	1,52		No	82,30	5,49	4,27	1926,68
#2 Gas					Fully grouted	1,52		No	12,19	5,79	2,13	150,65
Eagle								No	9,14	6,10	1,83	101,94
#2 Gas					Fully grouted	1,2192 and 1,8288		No	24,38	5,49	2,44	326,21
Coalburg								No	36,58	6,10	2,13	475,72
Coalburg					Tensioned	1,2192 and 1,8288		No	16,76	6,10	2,13	218,04
Dorothy								No	6,10	6,10	2,74	101,94
Coalburg	shale							No	18,29	6,10	1,83	203,88

Eagle	shale							No	5,49	4,57	1,52	38,23
Five Black	shale				Fully grouted and tensioned	1,83		No	10,67	5,79	1,83	112,98
Red Ash	shale				fully grouted	0,76		No	13,72	6,10	1,83	152,91
Powellton	shale							No	9,75	5,79	2,13	120,52
Alma	shale							No	9,14	6,10	2,44	135,92
Cedar Grove	shale							No	6,71	3,35	2,13	47,97
Eagle	shale							No	22,86	6,10	1,52	212,38
Splashdam	shale	sandstone	3,05	6,10	fully grouted	1,22			7,62	4,27	1,22	39,64
Splashdam Lower	laminated shale	sandstone	1,53	3,05	fully grouted	1,22	Timber		15,85	12,19	0,91	176,70
Banner Lower					fully grouted	1,52	2,4m cables		6,10	6,10	2,44	90,61
Banner Lower	gray shale	sandstone	3,05	6,10	fully grouted	1,52	1,8 by 2,4m cables		13,72	6,10	3,05	254,85
Banner Lower	slickensided shale	sandstone	3,05	3,05	tensioned	1,83			9,14	4,88	1,98	88,35
Banner Lower	slickensided	sandy shale	5,19		tensioned	1,83	2,4m & 3,6m cables		20,42	4,27	5,24	456,87
Lower Parson	shale	limestone	3,05	3,05	fully grouted and superbolts	1,524 and 2,4384			24,38	6,10	7,62	1132,67
Upper Parson	shale	sandstone	3,05	3,05	fully grouted and superbolts	1,524 and 2,4384			18,29	6,10	1,52	169,90
Mareker	laminated shale	shale	3,05	3,05	anchor	1,52	3m cables		6,10	5,49	5,24	175,35
Taggart	gray shale				fully grouted	1,22	2,4m cables		36,58	15,24	4,57	2548,52
Jawbone	shale	sandstone	1,07	3,05	tensioned	1,52			7,62	4,88	1,98	73,62

Tiller	shale	sandstone	1,07	3,05	tensioned	1,83	3m cables		9,14	5,49	2,44	122,33
Tiller	laminated shale	sandstone	3,05		tensioned	1,83	3m cables		9,14	6,10	3,05	169,90
Hagy Lower	shale	sandstone	3,05	3,05	fully grouted	1,52			6,10	6,10	1,83	67,96
Banner Lower	shale				fully grouted	1,52	3,6m cables		9,14	5,49	1,83	91,75
Banner Lower	shale				fully grouted	1,52	3m cables		18,29	5,49	2,44	244,66
Banner Lower	shale				fully grouted	1,52	3m cables		7,62	1,83	1,52	21,24
Banner Lower	shale				fully grouted	1,52	3m cables		18,29	5,49	2,44	244,66
Banner	laminated shale	shale	3,05	13,12	fully grouted	1,52	2,4m cables		27,43	6,10	3,05	509,70
Jawbone	shale	sandstone	3,05	3,05	fully grouted	1,52	2,4m cables		7,92	6,10	3,66	176,70
Jawbone	shale				anchor		2,4m cables		6,10	6,10	5,49	203,88
Kennedy	slickensided shale	sandstone	3,05	6,10	Fully grouted	1,07			10,67	7,62	3,66	297,33
Tiller	laminated shale	sandstone	1,83	21,35	Fully grouted	1,22	3,6m cables		9,14	6,10	3,05	169,90
Hagy	shale				Fully grouted	1,22			8,23	1,52	1,52	19,11
Imboden	laminated shale	sandstone	3,05	3,05	anchor, superbolts	1,83	3,6m cables		6,71	6,71	2,44	109,64
Dorchester	laminated shale	sandstone	3,05	3,05	Fully grouted	1,52	2,4m cables		6,10	6,10	3,05	113,27
Imboden	shale	sandstone	3,05	3,05	tensioned	1,52			16,76	5,49	1,83	168,20
Pocahontas #5	soft shale	laminated sandstone	1,22	3,05	Fully grouted	1,2192 and 1,8288	Timber		18,29	6,10	2,44	271,84
Pocahontas #5					Fully grouted	1,2192 and 1,8288	Timber		6,71	6,10	2,44	99,68
Pocahontas #5	laminated shale	sandstone	3,05	3,05	Fully grouted	1,2192 and 1,8288			12,19	5,49	2,13	142,72
Pocahontas #5	laminated shale	sandstone	4,83	3,05	Fully grouted	1,22			18,29	5,49	1,83	183,49

Pocahontas #5	laminated shale	sandstone	3,05		Fully grouted	1,22			12,19	4,27	1,22	63,43
Pocahontas #5	laminated shale	sandstone	3,05		Fully grouted	1,07			24,38	5,49	1,22	163,11
Wilson	shale				Fully grouted	1,22			15,24	6,10	3,05	283,17
Lower Banner	slickensided shale	shale	2,44		Fully grouted	1,52			4,27	3,05	1,68	21,80
Jawbone	shale	sandstone	0,92	3,05	Fully grouted	1,52			21,34	5,49	2,13	249,75
Jawbone	sandy shale	sandstone	0,92	3,05	Fully grouted and tensioned	1,22		Yes	6,10	5,49	2,13	71,36
Splashdam	laminated shale	sandstone	3,05	4,58	Fully grouted	0,91			9,14	6,10	1,22	67,96
Jawbone	laminated shale	sandstone	3,05		Fully grouted	0,91	Cribs		4,57	4,57	0,61	12,74
Jawbone	shale	shale	1,83	6,10	tensioned	1,83	3m cables		18,29	5,79	6,10	645,62
Splashdam	laminated shale	sandy shale	3,05	3,05	fully grouted	1,22	2,4m cables		42,67	6,10	2,44	634,30
Low Splint	sandy shale	sandstone	3,05	3,05	fully grouted	1,22			12,19	6,10	2,44	181,23
Low Splint	shale with coal streaks	sandstone	1,83	3,05	fully grouted	1,22			9,14	6,10	3,05	169,90
Low Splint	shale with coal streaks	sandstone	1,83	3,05	fully grouted	1,22			16,46	10,97	2,13	385,34
Wilson	shale				anchor	1,83	2,4m cables		7,62	4,57	2,13	74,33
Wilson	laminated shale	shale	3,05	3,05	tensioned	1,83	2,4m cables		6,10	6,10	3,66	135,92
Banner Lower	sandy shale	sandstone	3,05	3,05	fully grouted	1,22			6,10	6,10	1,83	67,96
Low Splint	laminated shale	shale	3,05	3,05	fully grouted	1,52			12,19	6,10	1,98	147,25
Low Splint	shale	sandstone	3,05		fully grouted	1,52	3m cables		6,10	6,10	3,05	113,27
Jawbone	shale	sandstone/s hale	4,58	4,58	anchor	1,83	3m cables		10,67	10,67	4,57	520,32

Wax Lower	shale	sandstone	3,05	3,05	fully grouted	1,22			18,29	5,49	3,05	305,82
Banner Lower	laminated shale	sandy shale	3,05	3,05	fully grouted	1,52			9,14	6,71	3,05	186,89
Banner	laminated shale	sandy shale	3,05	3,05	fully grouted	1,52	2,4m cables		10,67	6,10	2,44	158,57
Low Splint	laminated shale	sandy shale	3,05	3,05	fully grouted	1,52	2,4m cables		6,10	6,10	1,68	62,30
Pocahontas #3	laminated shale	sandy shale	3,05	3,05	fully grouted	1,83			7,62	6,10	1,83	84,95
Pocahontas #11	laminated shale	sandy shale	3,05	3,05	fully grouted	1,83	Truss bolts		30,48	6,10	1,83	339,80
Parsons	soft shale	shale	1,83	3,05	fully grouted		Cribs		9,14	6,10	2,44	135,92
Jawbone	sandy shale	sandstone	3,66	6,10	tensioned	1,83	2,4m cables		24,38	6,10	3,05	453,07
Jawbone	gray shale with slips	gray to black shale	1,53		fully grouted		2,4m cables		15,24	6,10	3,05	283,17
Tiller	sandy shale	sandstone	1,53	3,05	fully grouted	1,22			18,29	4,88	0,61	54,37
Tiller	sandy shale	sandstone	1,53	3,05	fully grouted		Cribs		13,72	6,10	1,52	127,43
Jawbone	slickensided shale	shale	6,10	6,10	anchor	1,52			11,58	5,79	1,68	112,45
Pocahontas #11	laminated shale	sandstone	3,05	3,05	fully grouted				13,11	19,50	1,07	272,65
Norton Lower	stack rock	shale	3,05	3,05	fully grouted	1,22			6,10	6,10	3,05	113,27
Lower Banner	shale				tensioned	1,83	3,6m cables		7,62	6,71	3,05	155,74
Banner	laminated sandy shale	sandstone	3,05	3,05	fully grouted	1,22			15,24	6,10	2,13	198,22
Imboden	shale	sandstone	4,27	4,27	fully grouted	1,22			24,38	5,79	2,44	344,33
Jawbone Widow	thinly laminated shale	shale	1,83	6,10	tensioned	1,83			10,67	1,83	1,83	35,68
Kennedy	slickensided shale	shale	1,37	3,05	mechanicals				9,14	6,10	1,37	76,46

Pond Creek	shale	sandstone and shale	3,05	15,25	tensioned	1,52			18,29	5,49	1,52	152,91
Pond Creek	sandstone		1,53		Fully grouted	1,22			4,57	3,66	1,52	25,49
Elkhorn #2	shale				Fully grouted	1,52	0,6m by 2,4m cables	Yes	12,19	9,14	3,05	339,80
Elkhorn #3	shale				tensioned	1,52	2,4m cables		9,14	5,49	1,83	91,75
Elkhorn #2	shale				Fully grouted	1,52	0,6m by 2,4m cables		12,19	9,14	3,05	339,80
Elkhorn #3	shale	sandstone	4,58	15,25	Fully grouted	1,22			6,10	6,10	2,44	90,61
Elkhorn #3	Shale				Fully grouted	1,22	0,6m by 2,4m cables	Yes	7,62	5,49	2,44	101,94
Elkhorn #3	Blue shale				Fully grouted	1,83			30,48	6,10	1,83	339,80
Elkhorn #3	Blue shale				Fully grouted	1,83			12,19	6,10	1,83	135,92
Elkhorn #3	Blue shale				Fully grouted	1,22			5,49	5,49	1,37	41,29
Elkhorn #3	Shale				Fully grouted	1,22	0,6m by 2,4m cables		7,62	5,49	2,44	101,94
Lower Eikhorn	Sandstone				Fully grouted	1,22			9,14	6,10	1,22	67,96
Pond Creek	sandstone	shale	3,05	18,30	Fully grouted	1,52			24,38	6,10	2,44	362,46
Pond Creek	sandstone	shale	3,05	18,30	Fully grouted	1,83	3m cables		27,43	6,10	1,83	305,82
Pond Creek	sandstone	shale	3,05	18,30	Fully grouted	1,83	3m cables		6,10	6,10	3,05	113,27
Pond Creek	sandstone	shale	3,05	18,30	Fully grouted	1,52			24,38	6,10	2,44	362,46
Pond Creek	sandstone	shale	3,05	18,30	Fully grouted	1,83			21,34	6,10	2,13	277,51
Pond Creek	sandstone	shale	3,05	18,30	Fully grouted	1,52			6,10	6,10	3,05	113,27
Pond Creek	sandstone	shale	3,05	18,30	Fully grouted	1,83	3m cables		6,10	6,10	3,66	135,92
Pond Creek	sandstone	shale	3,05	18,30	Fully grouted	1,83			12,19	6,10	2,44	181,23
Pond Creek	sandstone	shale	2,44	18,30	tensioned	1,83	2,4m cables		6,71	6,10	2,29	93,45

Pond Creek	sandstone	shale	3,05	18,30	tensioned	1,83	3m cables		27,43	6,10	1,83	305,82
Glamorgan	sandstone	shale	3,05	18,30	fully grouted	1,52	3m cables		6,10	3,05	2,44	45,31
Miller	sandstone	gray shale	4,88	3,05	fully grouted	1,52	2,4m cables		9,14	9,14	1,52	127,43
?	shale	sandstone	4,88	3,05	fully grouted	1,52	6 by 10' cables		21,34	6,10	3,66	475,72
Glamorgan	laminated sandstone	sandstone	3,05	18,30	fully grouted	1,52			6,10	3,05	2,44	45,31
Elkhorn #3	laminated sandstone	sandstone	1,83	6,10	fully grouted	1,22	2,4m cables	Yes	6,10	5,79	2,44	86,08
Elkhorn #3	shale and coal rider	sandstone	1,83	6,10	fully grouted	1,22	2,4m cables	Yes	18,29	6,10	2,44	271,84
Elkhorn #3	laminated shale	sandstone	1,83	6,10	fully grouted	1,22	2,4m cables	Yes	6,10	5,79	2,44	86,08
Williamson	Shale				fully grouted	1,22		Yes	15,24	5,79	1,52	134,51
Williamson	Shale				fully grouted	1,22		Yes	12,19	5,79	2,13	150,65
Williamson	Shale				fully grouted	1,22		Yes	15,24	5,79	1,52	134,51
Williamson	Shale				fully grouted	1,22		Yes	7,62	7,62	2,44	141,58
Williamson	Shale				fully grouted	1,22		Yes	42,67	6,10	1,83	475,72
Williamson	Shale				fully grouted	1,22		Yes	21,34	1,22	1,37	35,68
Pond Creek	Shale	sandstone	3,05	1,53	tensioned	1,52		Yes	21,34	6,10	2,13	277,51
Pond Creek	soapstone and shale	sandstone	2,44	3,05	fully grouted	1,52	2,4m cables	Yes	7,62	5,79	2,44	107,60
Pond Creek	shale and sandstone	sandstone	2,75	3,05	tensioned	1,52		Yes	6,10	6,10	2,74	101,94
Pond Creek	shale and sandstone	sandstone	3,05	18,30	tensioned	1,52		Yes	6,10	6,10	2,13	79,29
Pond Creek	shale	sandstone	3,05	18,30	fully grouted	1,52	1,2m by 3m cables	Yes	9,14	5,79	2,44	129,12
Pond Creek	shale and sandstone	sandstone	3,05	18,30	fully grouted	1,52		Yes	21,34	4,88	1,83	190,29

Pond Creek	shale	shale and sandstone	2,14	6,10	tensioned	1,52		Yes	12,19	5,79	2,13	150,65
Pond Creek	Shale				tensioned	1,83	1,2m by 3m cables	Yes	9,14	5,49	2,13	107,04
Pond Creek	shale and sandstone	sandstone	3,05	18,30	fully grouted	1,52		Yes	12,19	6,10	2,44	181,23
Pond Creek	shale and sandstone	sandstone	3,05	18,30	tensioned	1,52	1,2m by 3m cables	Yes	7,62	6,10	3,05	141,58
Pond Creek	shale and sandstone	sandstone	3,05	18,30	tensioned	1,52	1,2m by 3m cables	Yes	15,24	6,10	2,74	254,85
Pond Creek	shale and sandstone	sandstone	3,05	18,30	tensioned	1,52		Yes	12,19	5,79	1,52	107,60
Pond Creek	shale and sandstone	sandstone	3,05	18,30	tensioned	1,52	1,2m by 3m cables	Yes	9,14	6,10	2,44	135,92
Pond Creek	shale and sandstone	sandstone	3,05	18,30	fully grouted	1,52	1,2m by 3m cables	Yes	9,14	6,10	2,44	135,92
Elkhorn #3	shale and sandstone	sandstone	3,05	9,15	fully grouted	1,22		Yes	9,14	5,49	1,52	76,46
Elkhorn #3	shale	sandstone	7,63	7,63	fully grouted	1,52	2,4m cables	Yes	6,10	6,10	1,37	50,97
?	dark gray shale	gray shale	3,05	4,58	fully grouted	1,22		Yes	19,81	6,10	1,98	239,28
Hazard #4	Sandstone				fully grouted	1,09728'		Yes	9,14	4,88	1,22	54,37
Hazard #4	Laminated sandstone				fully grouted	1,07		Yes	7,62	6,10	1,37	63,71
Elkhorn #3	sandstone and shale	sandstone	3,05		fully grouted	1,07		Yes	6,10	5,79	1,22	43,04
Elkhorn #3	Shale				fully grouted	1,22		Yes	6,10	6,10	2,44	90,61
Hazard #4	Shale	sandstone	6,10	6,10	fully grouted with straps	1,22		Yes	12,19	8,23	1,52	152,91
Elkhorn #3	Shale	sandstone	6,71	1,83	fully grouted	1,22		Yes	6,10	4,57	1,52	42,48
Elkhorn #3	slate	slate and shale	1,53	91,50	fully grouted	1,22		Yes	9,14	8,84	1,52	123,18

Elkhorn ##	Shale	sandstone	6,71	18,30	fully grouted	1,22		Yes	18,29	7,62	1,68	233,61
Pond Creek	Shale	shale and sandstone	3,05	9,15	fully grouted	1,52		Yes	12,19	5,49	1,83	122,33
Fireclay	Sandstone				fully grouted	1,22	Cribs	Yes	21,34	5,49	2,44	285,43
Fireclay	shale	sandstone	4,58		fully grouted with straps	1,22		Yes	12,19	5,79	2,13	150,65
Elkhorn #2	shale				fully grouted	1,22		Yes	27,43	6,10	2,44	407,76
Elkhorn #2	shale				fully grouted	1,22		Yes	9,14	5,79	2,44	129,12
Hazard #4	laminated sandstoen	shale	3,05	15,25	fully grouted	1,83		Yes	15,24	6,10	3,05	283,17
Pond Creek	weak shale	firm shale and sandstone	3,05	3,05	fully grouted and chuck	1,8288 and 0,9144	3m cables	Yes	9,14	5,79	3,05	161,41
Pond Creek	shale	sandstone and shale	3,05	15,25	bolts			Yes	6,10	4,57	1,22	33,98
Lower Elkhorn	shale	sandstone and shale	3,05	15,25	fully grouted	1,83		Yes	15,24	15,24	2,74	637,13
Coalburg					fully grouted	1,22		Yes	9,14	9,14	1,83	152,91
Coalburg					fully grouted	1,22		Yes	27,43	6,10	1,83	305,82
Coalburg	slate	sandstone	0,92	9,15	fully grouted	1,22		Yes	10,67	3,66	6,10	237,86
Elkhorn #3	laminated gray shale	sandy shale	1,83	3,05	fully grouted	1,22		Yes	39,62	6,10	3,66	883,49
Elkhorn #3	shale	sandstone	3,05	30,50	fully grouted	1,22		Yes	21,34	9,14	1,07	208,13
Elkhorn #3	shale	sandstone	3,05	24,40	fully grouted	1,22		Yes	6,10	6,10	1,52	56,63
Elkhorn #3	shale	sandstone	3,05	24,40	fully grouted	1,22		Yes	6,10	6,10	1,52	56,63
Elkhorn #3	Slate				fully grouted	1,22		Yes	24,38	6,10	1,52	226,53
Elkhorn #3	sandy shale	shale and sandstone	3,05	15,25	fully grouted	1,22		Yes	27,43	5,79	1,98	314,74

Cedar Grove	shale	shale and sandstone	2,14	15,25	fully grouted	1,22		Yes	12,19	6,10	1,52	113,27
Glamorgan	slate	sandstone	1,37	16,47	fully grouted	1,22		Yes	9,14	5,79	1,37	72,63
Glamorgan	sandy shale	sandstone	3,36		fully grouted	1,22		Yes	15,24	5,49	4,57	382,28
Glamorgan	shale	sandstone	3,36	16,47	fully grouted	1,22	2,4m cables	Yes	9,14	6,10	1,98	110,44
Pond Creek	shale and sandstone	sandstone	3,05	18,30	fully grouted	1,22		Yes	18,29	6,10	1,52	169,90
Clintwood	Shale				fully grouted	1,22		Yes	12,19	5,49	2,44	163,11
Elkhorn #2	laminated shale	sandstone	3,05	3,05	fully grouted	1,83	3m by 4,2m cables	Yes	6,10	6,10	1,98	73,62
Elkhorn #2	shale	shale and sandstone	6,10	15,25	tensioned	1,52		Yes	12,19	5,79	1,83	129,12
Van Lear	sandy shale	sandstone	3,05	3,05	fully grouted	1,83		Yes	7,62	7,32	3,96	220,87
Elkhorn #3	sandstone and shale	shale	2,44	18,30	fully grouted	1,07		Yes	42,67	6,10	1,22	317,15
Elkhorn #1	laminated shale	sandy shale	1,53	4,58	tensioned	1,52		Yes	60,96	5,49	4,57	1529,11
Elkhorn #3	Sandy shale				fully grouted	1,22		Yes	18,29	5,49	3,05	305,82