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Paper

DESIGN PROTOCOLS OF CAVITIES CREATED BY WATERJET BOREHOLE MINING OF THIN-SEAM DEPOSITS

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ABSTRACT

The economic extraction of thin-seam coal deposits are often problematic due to several significant limitations associated with conventional mining methods, operating practices, and equipment. It appears that the most prudent way to extract these resources in a more economical way is through the development of technology to remotely extract these resources from the surface, where waterjet borehole excavation represents a novel approach. There are a number of technical challenges that must be overcome to advance the concept of in-situ waterjet borehole mining of non-soluble resources to a commercially viable stage. Paramount among these include the continued technical advancement of drilling and excavation systems, the mechanisms used to crush, bail, and transport cuttings from the borehole, the required instrumentation to effectively control and monitor the mining process, and a technical understanding between cavity formation and stability for a given set of operating characteristics and geomechanical rock properties. Understanding the structural dynamics of these cavities is a key element in designing a mining system capable of sufficient resource recovery to economically justify the capital investment. The unintended collapse of these cavities could potentially result in the detrimental loss of mineral reserves, as well as surface subsidence.

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1. INTRODUCTION

The economic extraction of thin-seam coal deposits with thicknesses of less than 1 meter are often problematic due to several significant limitations associated with conventional mining methods, operating practices, and equipment. Mines with low-seam heights are endemic of operations that possess low labor productivities, high operating costs, and relatively small production capacities. Furthermore, the ability to implement new equipment and automation in order to efficiently exploit these thin-seams is hampered by the limited cash-flow positions of most of these operations and the inability to amortize their high costs over a sufficiently large resource base. Consequently, these mines are usually small, labor intensive, and rely extensively on used and rebuilt equipment modified to operate in these challenging work environments.

Britton [2] has investigated the productivity of thin-seam mining, where he attributes the inherent low productivity of these operations to the small tonnage produced per unit length of linear advance and the challenges associated with mining in a confined work environment, particularly with regards to material handling, unit operations at the face, and logistics. Another pragmatic issue identified by Britton is ventilation, where obtaining the required airflow at specific work areas can be difficult due to the obstruction of a large percentage of openings by equipment.

Fotta et al [3] did research to identify the types of injuries common to operating mines that exploit thin-seam resources. Due to their research objectives, longwall operations and large mines that employing more than 50 workers were specifically excluded from this study. Fotta found a direct correlation between working height and worker safety principally attributed to restricted employee mobility, reduced vision and poor posture, and limitations of using protective canopies and other common engineering safety devices/controls as a consequence of space constraints. [3]

Building upon Fotta’s research, Peters et al [4] studied significant potential hazards that are substantially dependent upon coal seam height. The study focused on accidents that occurred between 1990-1996, where 117 workers were fatally injured at small (non-longwall) underground bituminous coal mines. The three types of incidents that were responsible for a preponderance of these fatalities were associated with: 1) roof falls, 2) powered haulage, and 3) machinery. Based on the same research, the six most prominent types of incidents responsible for non-fatal day’s lost (NFDL) accidents were: 1) handling materials, 2) machinery, 3) powered haulage, 4) slips and/or falls of person, 5) roof falls, and 6) non-power hand tools.

Figures 1 and 2 illustrate the fatal and non-fatal day lost incident rates for underground coal mines between 1998-2008. Based on the number of employees, U.S. underground coal mines have been divided into two distinct categories: small (employing less than 50 employees) and large (employing greater than 50 employees). Using data obtained from the Mine Safety & Health Administration (MSHA) Injury Experience Reports for Coal, Figure 1 shows, with the exception of 2007, the fatal incident rates for small underground mines are higher as compared to larger operations.

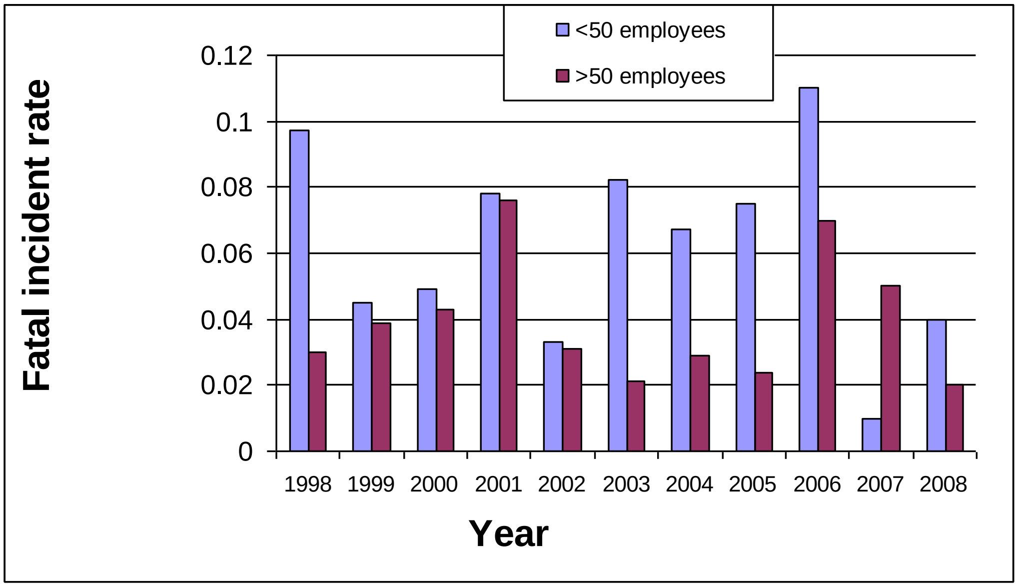

Figure 1. Fatal incident rate for small and medium/large underground coal mines for 1998-2008. [1]

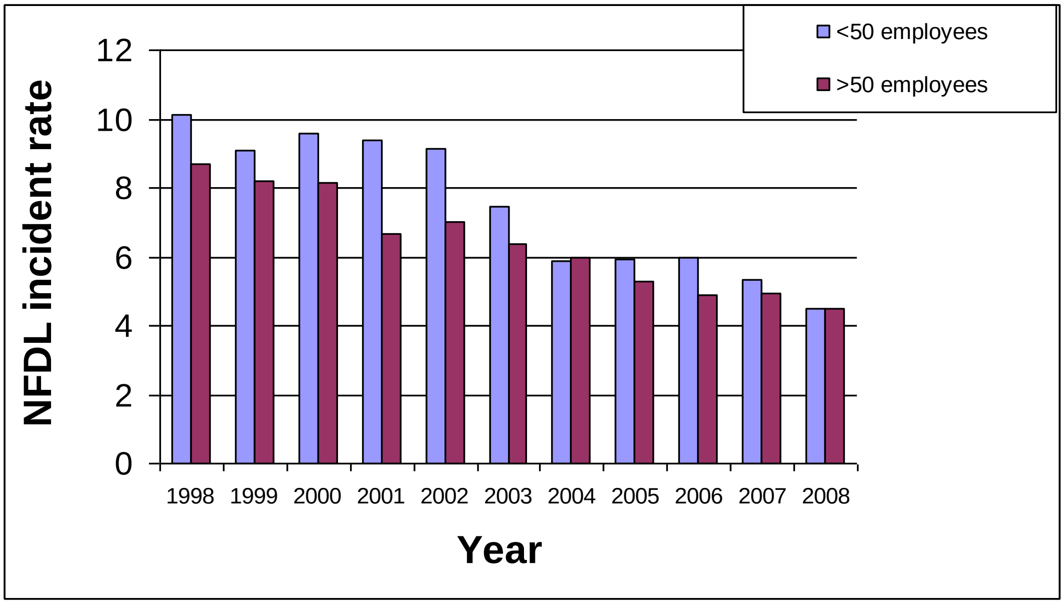

Figure 2. Non-fatal day lost incident rate for small and medium/large underground coal mines for 1998-2008. [1]

During 2008, an estimated 5.2 million tons of coal were produced in the U.S. from thin seams deposits with operating heights less than 1.06 m (42 inches). This represents approximately 14.5% of the total U.S. underground coal production. Of the 657 underground coal mines operating in 2008, nearly 70% of them have less than 50 employees. This is consistent with previous research that indicates 94% of mines operating in seams of 1.06 m or less employed fewer than 50 people [2].

Papas et al [5] conducted research that focused on injuries attributed to roof and rib falls that occurred during the period 1995-1998 in all the U.S. underground coal mines. As expected, this study concluded that mines operating in thin seams (< 1.09 m) tended to be smaller scale operations that solely used room-and-pillar extraction methods. The research showed that small mines in thin seams had a ground fall fatality rate that is 44% greater than the national average (Figure 3), while small mines operating in thick seams had a ground fall fatality rate that is 53% lower than the national average. The consequence of this data has led to the conclusion that small mines in themselves are not a contributing factor in the incidence of rock fall fatalities, whereas seam height appears to be a dominant and influential factor. The study also indicates that the potential root-causes of these fatalities largely stem from the lack of engineering controls specifically suited for these small, low seam environments, such as protective cabs and canopies on operating equipment. In these operating environments, workers are especially at risk should a massive roof or rib failure occur.

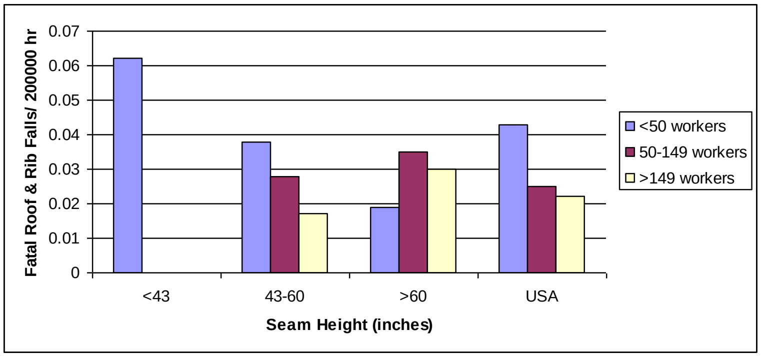

Figure 3. Roof and rib fall fatality rates by mine size and seam height for room-and-pillar mines, 1995-1998. [5]

Despite these challenges, a number of companies are focusing on ways to exploit these narrow, tabular deposits. In specific geographical locations whose economies are heavily dependent on coal mining, the depletion of thick seams have placed greater pressure to develop innovative technologies to economically recover coal resources from much thinner deposits. An examination of world coal resources also shows that a substantial percentage is contained in thin-seam deposits. Shiua [10] estimates that approximately 96% of China's total coal production is from underground mines, where more than half of these reserves are reside in thin seams less than 0.7m. As such, these thin-seams are of strategic importance and represent a significant source for supplying the country's future energy needs. However, advancements in safety and extraction methods are requisites for exploiting these resources. Coupled with competing demands for surface land-use, it appears that the most prudent way to achieve these objectives is through the development of technology to remotely extract these resources from the surface. Displacing workers from the underground work environment will eliminate the inherent hazards of mining these deposits and reduce the direct costs associated with ventilation, support, and equipment.

Over the last three decades, a number of researchers have been working on the development of in-situ applications for the extraction of coal and other economic minerals through boreholes. For example, Dr. George Savanick of the U.S. Bureau of Mines conducted experiments using in-situ borehole mining equipment on several different commodities including coal, gold, and industrial minerals, beginning in the mid-1980s [6]. His test results for the borehole mining of coal showed that it was technical feasibility but not economically viable at the time. Through his work, several advantages associated with this method were quantified, including improved worker safety and the mitigation of adverse environmental impacts [6]. Wiley et al [8] also identified several advantages associated with borehole mining including: safety, the ability to work in remote areas, a reduction in adverse environmental impacts, greater mobility, increased selectivity, lower capital cost, improved system simplicity, and the ability to operate in a variety of ground conditions. According to his work, borehole mining could economically compete with conventional methods in areas that possess tabular structures, low ore grades, complicated hydrogeological conditions, hazardous operating conditions, and inaccessible locations. Wang and Miller [7] also identified potential reductions in the cost of social and environmental impacts over conventional mining systems in numerous applications.

Despite these potential benefits, there are a number of technical challenges that must be overcome to advance the concept of waterjet in-situ borehole extraction of non-soluble resources to a commercially viable stage. Paramount among these includes the stability of the induced cavity during the mining process. In several empiric experiments and field trails, waterjets have shown the ability to excavate cavities that are inherently unstable for a given rock type because of geometry, cross-sectional dimensions, alteration/damage to the wall-rock, or applied stress as a consequence of the mining sequence. The unintended collapse of these cavities could potentially result in the detrimental loss of mineral reserves, as well as surface subsidence, the incidence of significant dilution, and the loss of equipment. In addition, adverse alterations in cavity geometry caused by failure in the surrounding host rock will significantly hamper the ability to recover and bail fragmented mineral from the borehole. Cavity stability, in turn, is the product of a complex set of multi-dimensional variables that include in-situ stresses, rock properties, cavity geometry, time, and the rate and manner of excavation. A number of additional confounding issues associated with the proposed excavation methods (e.g., fluid pressurization of the cavity) may also adversely influence the stability of these cavities, where their potential effects need to be quantified [11].

2. DEFINITION OF BOREHOLE MINING METHOD (BHM)

In general terms, in-situ mining is defined as the physical extraction of the valuable components of a mineral resource through a borehole. In the context of this paper, Borehole Mining (BHM) is defined as a remotely operated method of extracting (mining) mineral resources through one or more strategically placed boreholes by means of high pressure fluid jets. This process can be conducted through a variety of operating configurations and drilling platforms, including conventional surface locations, sites within existing mines (both open pit and underground), and from floating vessels/rigs. A borehole is drilled from the surface to a desired depth, where the actual mining process will take place. After the hole has been drilled, a casing column is then inserted into the hole. The purpose for using casing depends on the method in which the cuttings are bailed (removed) from the hole. In most conventional applications, the casing provides hole stability, minimizes material loss, and reduces the potential for dilution caused by wall erosion or borehole failure. Since a cavity is formed as part of the normal mining process, a casing shoe is strategically positioned within the seam. Similarly, an ejector is situated at the bottom of the projected cavity to collect the excavated material and an inflatable packer is generally placed above the seam to regulate borehole pressure and bailing velocity. The BHM excavation tool is mounted to the drill string and is oriented relative to a predetermined excavation strategy [6, 7 and 8]. Figure 4 illustrates a cross-section of a conventional borehole mining system [9].

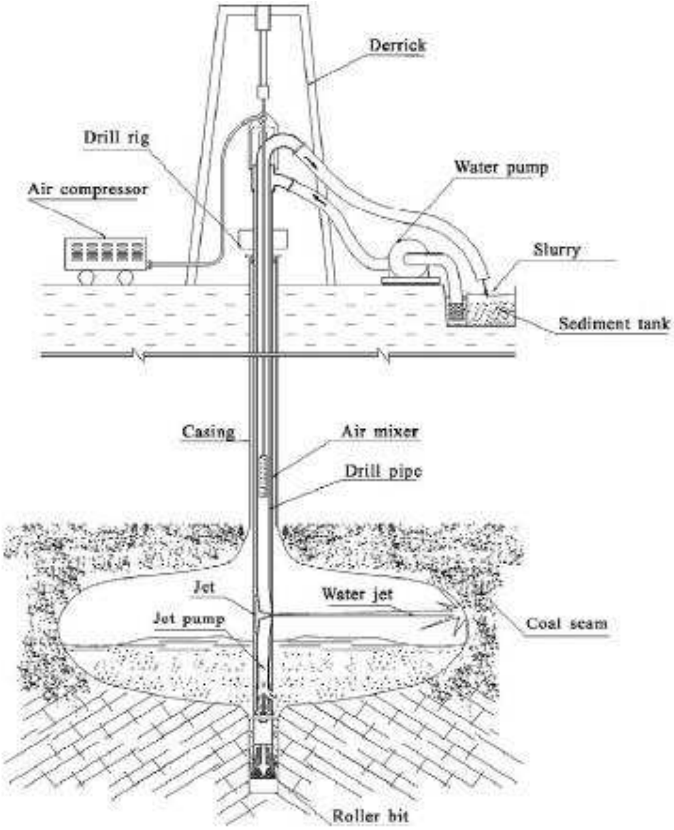

Figure 4. In-situ borehole mining procedure [9].

3. EFFECT OF CAVITY DIMENSION, INTERNAL PRESSURE, DEPTH OF COVER AND HORIZONTAL STRESS

The ultimate objective of this research was to establish a set of design protocols (guidelines) for estimating optimum cavity geometry and orientation for several critical excavation and geological factors. Based upon the positive results of the literature search and in an effort to address one of the prevailing technical challenges impeding the commercial applications of borehole mining in coal, a finite difference method (Flac2D) has been applied to do a parametric sensitivity study to investigate the effect of several parameters like internal pressure, cavity size, and in-situ stress, on the stability of a cavity developed through excavation of a mineral resource during borehole mining. In this stage, the research was focused on delineating the impact of critical factors associated with maintaining cavity stability during the mining process and how it pertains to the development of a design protocol.

This section describes the process of performing a stress analysis of a cavity excavated by BHM, and includes consideration of fluid pressurization of the cavity periphery. To accomplish this analysis, a finite difference method (Flac2D) was used. Figures 5 and 6 illustrate the geometry of the models. As Figure 5 shows, depth of cover, cavity length, and cavity height are represented as

H, L and D, respectively. To simplify the analysis, each side of the cavity is modeled independently and the application of internal fluid pressure is applied to only one side of the excavation. Figure 6 shows how internal pressure is applied inside the cavity.

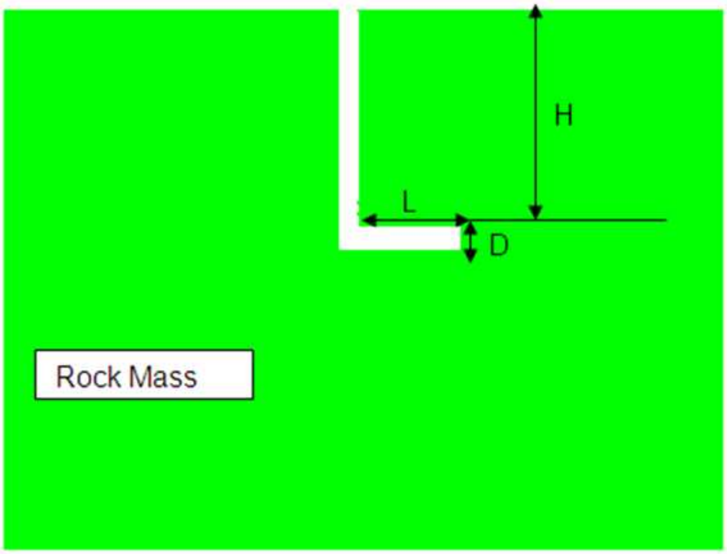

Figure 5. A view of model geometry [11].

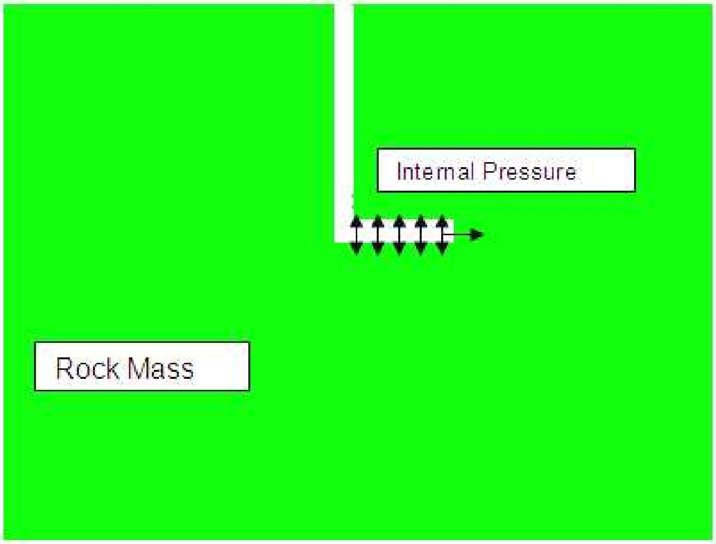

Figure 6. A view of under internal pressure (pressurization) [11].

Table 1 presents the mechanical rock properties that were applied in the models. For this study, the rock is assumed to be a homogeneous, isotropic material with no internal structure (e.g., bedding or jointing). The vertical in-situ stress is assumed to be gravitational, and equal to the unit weight multiplied by depth.

Table 1. Input mechanical properties [12].

Density	2700 kg/m^3
Elastic modulus (E)	11 Gpa
Poisson's ratio (v)	0.3
friction angle (φ)	14.4°
cohesion (c)	38.4 MPa
tensile strength (σ_t)	14.4 MPa

While the impact of groundwater flow has been neglected in this analysis, the effects of pore pressure were considered. The CONFIG GW command and a groundwater bulk modulus of 1.9 GPa were used in this case. The density and tension limit of the water were assumed to be 1000 kg/m^3 and 2000 Pa. respectively, and the SET flow function was turned off in order to exclude groundwater flow. The INITIAL PP command sets the initial pore pressure distribution for this case. The geometry of the model was 60 × 120 m which was made of 30 × 60 grids. The modeling sequence consists of the following stages:

- Establish equilibrium conditions to initialize stresses.
- Excavate the borehole and initiating a cavity in horizontal direction.
- Add internal pressure to the cavity roof, floor and side-walls, and cycle to equilibrium.
- Alteration of different cavity sizes under different pressures and depth were modeled.

The bottom and sides of the mesh are fixed in both x and y directions. In addition, since the borehole will likely be cased in the actual application, the walls of the borehole were also fixed. The height of the cavity was considered as one grid equal to 2 m. Four different values were considered for cavity length ranging from 2 to 20 m (i.e., 2, 6, 10 and 20 m). The internal pressure values were selected as 1.5, 7.5, 22.5 and 75 MPa. The reason for choosing this range was to observe the sensitivity of different internal pressures on the maximum principal stress. In this analysis, two different depths (i.e., 30 and 40 m) and the ratio of horizontal to vertical effective stress (1.0) were also assumed. Figures 7 and 8 illustrate the maximum principal stress around the cavity roof for different internal pressures, cavity length, and depth of cover.

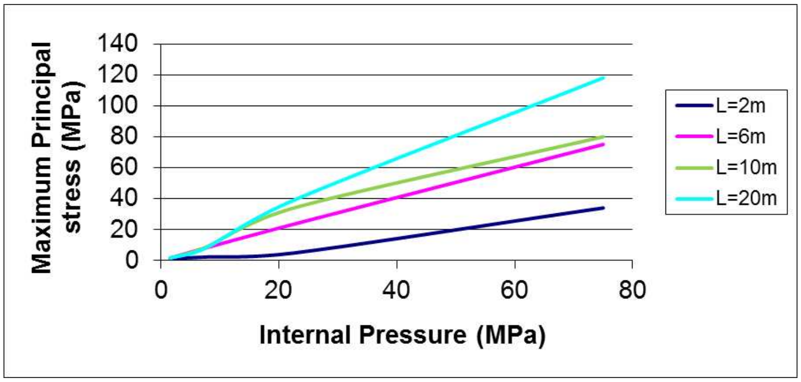

Figure 7. Maximum principal stresses versus internal pressure for different cavity length for depth of cover of 30 m [11].

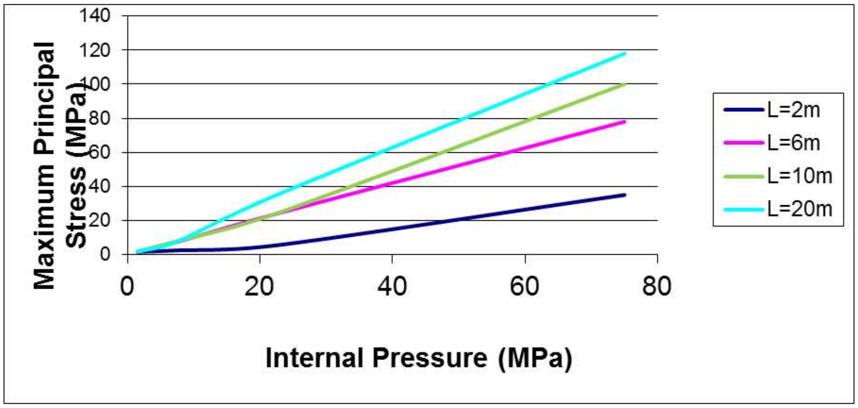

Figure 8. Maximum principal stresses versus internal pressure for different cavity lengths for depth of cover of 40 m [11].

As Figures 7 and 8 illustrate, increasing internal pressure and cavity length will significantly increase the induced maximum principal stress. Depth of cover plays an important role, but is not as significant as internal pressure and cavity size. As shown in the figures, situations involving low applied internal pressure (less than 5 MPa) will generate similar principal stresses for a variety of cavities size. As the figures illustrate, cavities with smaller dimensions are subject to fewer impacts derived from internal pressures as compared to larger cavities.

The influence of different values of K (horizontal stress/vertical stress) was also studied. While the range of different K values did not have significant effect on the maximum principal stress around the cavity; the difference between the maximum and minimum principal stresses changed significantly around the cavity periphery. Figure 9 illustrates the principal stress difference (σ_1- σ_3) for different values of K. Two different cases with internal pressure of 7.5 and 20 MPa were modeled, where cavity width was held constant as 10 m. As Figure 9 shows, increasing K will decrease (σ_1- σ_3) around the cavity roof corner. This implies that increasing the horizontal stress will result in a decrease of the induced shear stress at the cavity roof corners. According to Figure 9, increasing the internal pressure inside the cavity will translate to an increase in (σ_1- σ_3).

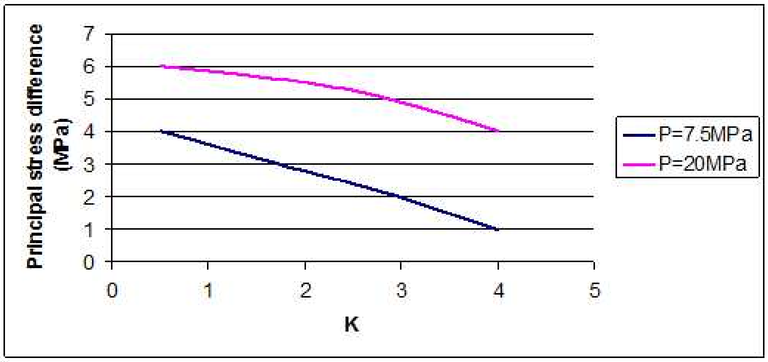

Figure 9. Principal stresses difference (σ_1- σ_3) versus different values of K [11].

Figures 10 to 14 show the effective principal stress before excavation (after stress is in equilibrium) and borehole excavation (before applying pressure) for a variety of cavity lengths (radii) (2 m, 10 m and 20 m). The internal pressure applied inside the cavity was 7.5 MPa. The rationale was that

7.5 MPa will give a more meaningful result as compared to 1.5, 22.5 or 75 MPa because an internal pressure of 1.5 MPa does not have a significant effect and that internal pressures of 22.5 and 75 MPa cause some failure. Depth of cover was held constant at 30 m. As seen in Figure 10 (before excavation), the major principal stress is vertical. As defined, these stresses linearly increase with depth. Figure 11 illustrates the effective principal stresses after the excavation was made and stresses have reached equilibrium, but prior to applying pressure around the cavity. It is apparent that the principal stress tensors rotate about the circumference of the excavation for a distance of approximately 1 cavity height.

Figures 12 to 14 illustrate the effective principal stress distribution for the cavity length (radius) of 2, 10 and 20 m under 7.5 MPa internal pressures. Comparing the unexcavated to excavated stresses, it can be seen that the maximum principal stress has increased around the cavity. Changes in principal stress tensor direction between the unexcavated and excavated states represent shear stresses due to excavation. As these figures indicate, the tensile-stress region expands as the cavity size is increased.

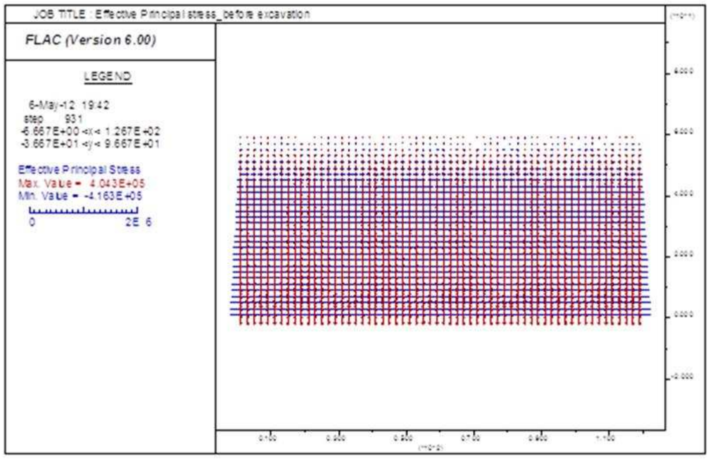

Figure 10. Effective principal stresses under gravitational loading.

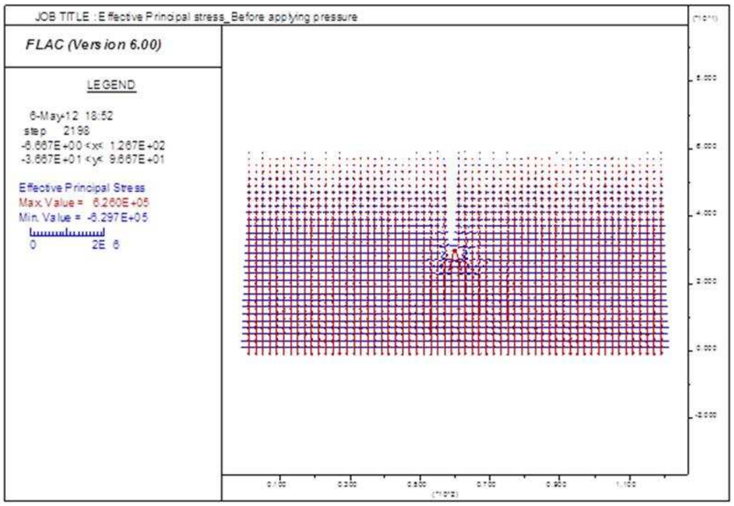

Figure 11. Effective principal stresses after borehole excavation and cavity initiation.

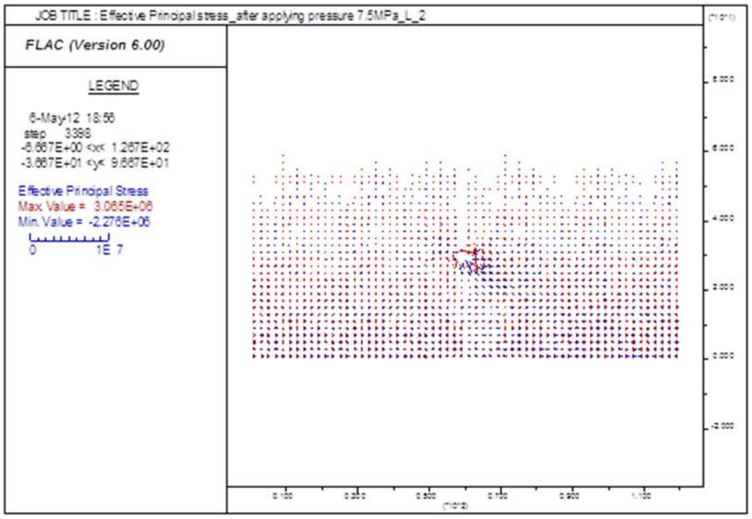

Figure 12. Effective principal stresses for cavity length of 2 m and internal pressure of 7.5 MPa.

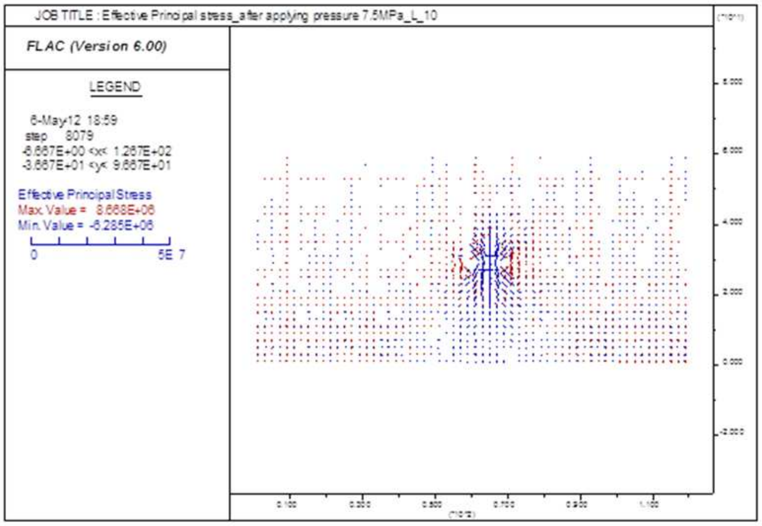

Figure 13. Effective principal stresses for cavity length of 10 m and internal pressure of 7.5 MPa.

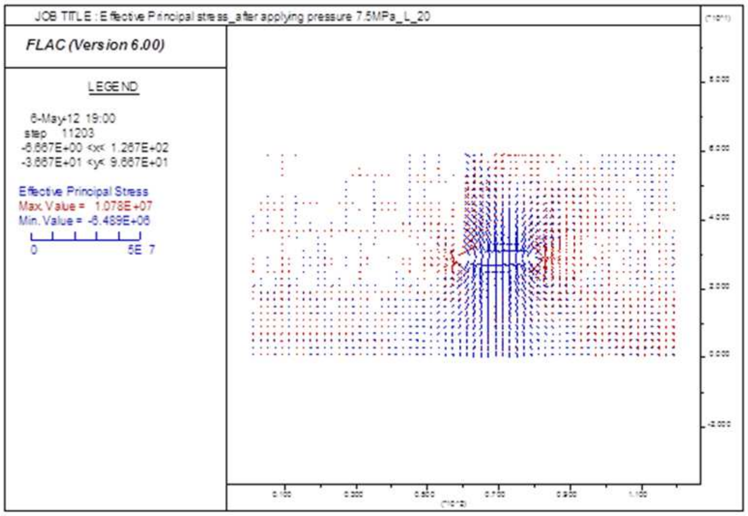

Figure 14. Effective principal stresses for cavity length of 20 m and internal pressure of 7.5 MPa.

4. SUGGESTED ALGORITHM TO PREDICT THE MAXIMUM CAVITY SIZE

Figure 15 presents a suggested algorithm for applying two dimensional finite difference method in order to predict the maximum cavity size that can be obtained without stability concerns.

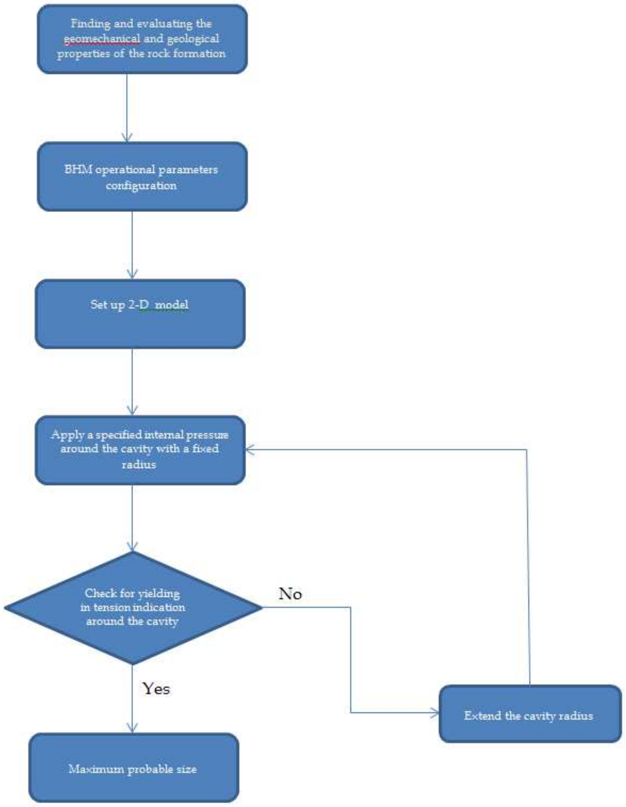

Figure 15. General design methodologies by applying finite difference method for prediction the maximum cavity radius [13].

5. OBSERVATIONS AND CONCLUSIONS

Several models were analyzed using Flac2D to perform a parametric study of factors that could potentially impact the borehole mining process, whereas information derived from the literature was useful in identifying several parameters that could possibly affect cavity design and the mining process. The results and observations of these studies (numerical modeling and literature search) led to the following proposed protocol design for the creation of stable cavities during waterjet borehole mining:

- While mitigating premature roof collapse is the primary motivation behind this research, it is also desirable for large cavities to collapse (fail) after the completion of mining so that adjacent cavities and pillars (segment between cavities) will be de-stressed. In some cases, coal seams lie in soft strata, such as claystone. These seams are usually characterized by geologically younger coking-coal deposits. Rapid extraction of the cavity may prevent development of accelerated deformation and collapse of cavity roof before coal has been extracted. The following are the general precautions that need to be considered regarding the immediate roof of a cavity as derived from literature search:

    a) Conglomerate: highest strength in the series of rock types that can be associated with a coal bearing strata,
    b) Sandstone: often resistant to caving after coal extraction,
    c) Siltstone: will usually cave after coal extraction,
    d) Shales and mudstones: susceptible to moisture, and may cave before coal extraction is completed,
    e) Clay rocks: often show low strength and higher moisture content with very low bearing capacity,
    f) Limestone: usually of moderate strength and good caving properties,
    g) Dolostone: similar properties to limestone,
    h) Shaly limestone: characteristically possess lower strength. Silty limestone is similar to shaly limestone and possesses lower strength.

- According to literature survey, if the immediate roof is thick and consists of strong sandy shale or sandstone, conglomerate and limestone, it can be left unsupported for extended period of time (up to 8 hours).

- Increasing internal pressure and cavity length will significantly increase the induced maximum principal stress around the cavity. Increasing internal pressure inside the cavity will also increase the induced shear stress at the cavity roof corner. In cavities with smaller dimensions, the impact of internal pressures is less than those with larger geometries. Depth of cover plays an important role, but in the case of shallow depths (below 40 m) it is not as significant as internal pressure and cavity size.

- During modelling, no plastic or shear yielding was observed for cavity radii of 2 m or less, even in environments with higher internal pressures. By keeping internal pressure up to approximately 10 MPa, no plastic and shear yielding were observed in all the modeled cavities (i.e. radii of 2, 6, 10, and 20 m).

- Applying internal pressure of 75 MPa caused plastic or shear yielding in all the cavities.

- Depending on the geomechanical properties of the rock formation (intact rock with the geomechanical properties similar to those outlined in Table 1 and a cavity height of 2 m), cavity radius of 10 m was determined to be the maximum size that could be reached without increasing stability issues, provided the internal pressure did not exceed a maximum of 30 MPa. It was observed that applying internal pressure of more than 30 MPa would induce tension failure around the cavity at a radius of 10 m. Applying internal pressure of 35 MPa will limit the cavity radius up to 6 m. In practice, the maximum borehole mining cavity radii has been empirically determined to be 26 ft (7.9 m) in sandstone.

- Designing a cavity with a radius of more than 10 m without having stability problems requires applying less internal pressure. In order to reach a cavity radius of 20 m, the internal pressure shall not exceed 10 MPa. Applying small internal pressure (extraction and pressurization) may have technical challenges associated with shorter standoff distance and material removal [13].

- The influence of changing pore pressure on the effective stress distribution, and the extent of the tensile stress region, were determined to be minor. However, variation in effective stress will impact permeability, and will increase the gas flow as a function of increasing permeability. The absolute permeability in coal can vary due to changes in the pressure of the formation. While borehole mining underwater has the advantage of providing additional roof support during the excavation process, the standoff distance that the waterjet can reach effectively will be reduced dramatically influencing the economics. As such, waterjet borehole mining is preferred in deposits above the water table in unsaturated environments.

- Cavity cyclic pressurization (bailing) will cause the stress concentration to move from cavity roof to the side-wall and corner. However, since negative pressure values are relatively minor compared to the original applied internal pressure, it should not impact cavity stability significantly.

- Increasing the horizontal stress will decrease the induced shear stress at the cavity roof corners.

- One of the major concerns in the design of borehole mining systems is the evaluation of cavity stability based on stress concentration and relaxation around the extraction area. The stress concentration generally depends on two parameters: the volume of removed coal and the load transfer to the cavity face as a consequence of mining. Cavity stability can be maintained by caving the mined-out area before the stress concentration on the face becomes critical. Designing suitable cavity shape and extraction orientation can be mitigating factors. Two extraction strategies under different k values, and different cavity shapes were studied.
- Reaching final optimum cavity size by using horizontal slices extraction has less stability concerns as compare to using vertical slices.

- In a borehole mining design, leaving the side walls in an arch shape (configuration), will increase the stability.

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