SINKHOLE RISK MANAGEMENT PROCESS WITHIN THERMAL COLLIERIES: A PRACTICAL APPROACH THEREOF

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DECLARATION

I declare that this research report is my own unaided work. It is being submitted to the Degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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(Signature of Candidate)

Signed on the ……………………….day of ………………………year………………………

at Braamfontein, Johannesburg

ABSTRACT

Previously undermined areas pose a significant challenge to mining by opencast due to the risk of sinkhole occurrence. In order to optimise reserve utilisation as well as safeguard personnel and equipment there was need to develop a “Sinkhole Prediction Model” to assist in the prediction of areas prone to sinkhole formation. The aim of this research therefore was to develop a “Sinkhole prediction tool” with a view to pre-identifying areas of potential sinkhole hazard to inform better controls to assist in mining these areas safely. This was done utilising the current Hill (1996) caving height method culminating in the development of a hazard index model dividing the mining zones into high and low hazard. These areas were colour coded Red (High hazard) and Green (Low Hazard).

The “Sinkhole Prediction Model” evolved to include over hundred sinkhole incidences that were statistically analysed to firm up on the robustness of the Prediction Model capabilities. The Hill (1996) caving height formula was discounted after the statistical analysis indicated that a good prediction model lies in the interrogation of site specific data.

The outcome of the work conducted in this research report indicated a 97% correlation between the refined “Sinkhole Prediction Model” and the actual sinkhole occurrence at the Anglo American case study area (Mine X). Various refinements inclusive of lithological assessments, blast and drilling reconciliations as well as the implementation of the roughening up quality audits led to the implementation of a robust sinkhole management process that has managed to consistently assist in safeguarding equipment and personnel thus allowing for coal extraction optimisation in areas that could have been written off due to the sinkhole hazard. This risk can only be eliminated by mining the areas with the sinkhole risk.

Currently the method is being impacted by significant roughening up cost incurred in a drive to make the areas safe to allow for coal extraction. The roughening up process on average costs R3.5 million per sinkhole and is a function of the number of sinkholes found, which translates to an equivalent cost of R7 / sales tonne. The current sinkhole prediction model being employed in deficient in that it cannot pinpoint the actual location of the void in the area previously undermined by bord and pillar and this is a great limitation of this report. Various geophysical techniques were pursued to assist in the precise identification of the actual sinkhole spatially. This process was aimed to reduce the roughening up cost (entire block stabilisation) as opposed to targeted sinkhole excavation and stabilisation. This process proved futile as the void identification systems are highly incapable of identifying the voids /

sinkholes spatially (x, y and z coordinates) to assist targeted sinkhole treatment as a result of the following:

- System inability to penetrate areas comprised of highly conductive strata such as clays.
- Inability to distinguish between the underground voids and geological anomalies such as dykes.
- Not suitable for penetrating wet strata.
- Impacted by noise interference from mining machinery.

The major result of this research is the establishment of a site specific “Sinkhole Prediction Model” that can generate hazard plans in real time thus informing the management on areas associated with a potential sinkhole hazard. The hazard plans can be generated timely and decisions made to facilitate safe coal extraction in areas of high sinkhole hazard.

This has culminated in a robust sinkhole management process within the group that has managed to eliminate the risk of personnel and equipment exposure at Mine X. The roughening up process is accepted as the primary sinkhole mitigation or rehabilitation process with the need to work towards reducing the roughening up costs through development of the tool capable of precisely identifying the voids routinely to facilitate targeted rehabilitation. Significant research is required in this area as the mining environment is comprised of strata that currently cannot support the use of real time void identification to facilitate targeted void identification and rehabilitation. There is also merit in the future to formulate the database capable of assisting in the prediction of sinkholes in the Witbank coalfield as well as assist in robust management of mining boundaries across the different mining houses. The system implemented at Mine X is currently being deployed to other operations in the group where modification will be made to match the site specific conditions.

Future research into understanding the sinkhole occurrence dynamics is quite crucial if targeted rehabilitation is to be achieved for cost reduction and mining sustainability. A combination of the understanding of the sinkhole occurrence driving mechanisms in conjunction with use of modelling packages such as ELFEN (a hybrid Modelling) tool will go a long way in enhancing the development of precise sinkhole prediction point in space.

To Ethel, Dasrey, Raphael, Cuthbert and Clyde.

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GLOSSARY OF TERMS

Bords	−	Refers to an open area underground between the pillars which is created by the extraction of coal.
Cavities	−	Refer to definition of Voids.
Hards	−	Refers to the consolidated material that can only be loosened by blasting and can be excavated mechanically by the dragline or excavator.
Lithology	−	Refers to the different rock types forming the overburden and lies above the top most economical seam.
“Live”	−	Refers to the direct use of top soil from where it’s being pre-striped to the area being rehabilitated.
Mining Window	−	A theoretical zone that defines the active mining area in the mining value chain, where active exposure and extraction activities are taking place.
Overburden	−	Refers to different rock units lying above the mineable horizon / A combination of material layers that lie between the upper most economical seam and the surface
Parting	−	A geologically competent layer usually found between two coal seams
Pillar	−	A solid ground of coal left during the underground coal extraction to serve as a support medium of the roof, thus maintain the stability.
Rehabilitated area	−	refer to roughening up
Roughening / rough up	−	The process of stabilising an area with a high potential for sinkhole formation. It is mostly a truck and shovel activity that is aimed at probing for sinkholes, that have

	formed due to underground workings and lie within the overburden. When sinkholes are encountered they are opened up, then filled up and compacted to stabilise the area prior to declaring the area safe to allow for drilling and overburden exposure to take place.
Sinkhole	− The term sinkhole is a loose definition referring to the any depression occurring on surface areas affected by mining activities and caused by failure of bords, surface collapse to pillar failure, localized depressions on rehabilitated ground, settlement of old rehabilitated areas / concealed shafts, any erosional or weathering related collapse and any cracks / cavities that may appear after blasting.
Strata	− Refers to the different layers of the material forming the overburden and lies above the top most economical seam.
Weathered	− Refers to the unconsolidated composition of the overburden material that is not capable of freestanding and is mechanical diggable by the Dragline or excavator.
XCM	− Refers to a set of instructions that facilitate data calculation, reporting and manipulation.
XPAC	− Refers to the mining modelling software, the actual meaning of the letters I do not know. Will keep finding out.

LIST OF ACRONYMS

AmCoal HI	Anglo American Coal Hazard Index
GPR	Ground Penetration Radar
LOM	Life of Mine
MASW	Multichannel Analysis for Surface Waves
MC	Mining combined
OVB	Overburden
S1	No.1 Seam
SHIP	Sinkhole Hazard Identification Process
TVR	“TerraVision Radar”
UCS	Uniaxial Compressive Strength
XCM	XPAC Command Module

1 INTRODUCTION

1.1 Background

Most coal mining companies in South Africa are increasingly finding it difficult to maintain sustainable profit margins due to increasing operational costs and decreasing export prices as well as constant domestic coal prices. A number of initiatives aimed at curbing the eroding profit margins among others, includes extraction of coal reserves locked up in the previously mined underground areas utilising strip mining methods. This drive to expand surface mining into previously mined underground areas is associated with significant safety and environmental risks such as subsidence, water pollution and spontaneous combustion of coal.

Amongst all of the above mentioned risks, safety is seen as the most predominant risk associated with subsidence requiring efforts to ensuring utmost personnel and equipment safety. Personnel and equipment safety is impacted by development of subsidence over areas of previously mined underground workings.

Subsidence refers to the settlement of the earth' surface caused by natural or man induced modifications of the underlying supporting structure (Stingelin et al, 1975). This is essentially a direct consequence of settlement of the supericumbent strata overlying the void left underground from the extraction of the valuable mineral for example coal. The impact of surface subsidence due to underground mining has long been recognised as having a detrimental effect to life and personnel. Concerted efforts made in the field of subsidence engineering concentrated on total coal extraction (longwall mining) as opposed to bord and pillar mining (partial extraction) system due to the complexity of subsidence prediction associated with bord and pillar mining (Singh, 1986). Longwall subsidence prediction is an established science with controls in place to mitigate the risk associated with these abandoned workings (Whittaker and Reddish, 1989). Longwall coal extraction methods in South Africa constitutes approximately nine percent of the total coal underground mining with the bulk of the abandoned underground coal mines being bord and pillar (Canbulat and Ryder, 2002). Although abandoned longwall mines exist these mines have well known means of controlling the risk as opposed to the sudden occurrence of the sinkholes. It is often the bord and pillar workings that cause the majority of subsidence damage due to the formation of sinkholes.

Sinkholes are the most pre-dominant type of subsidence in South African coal mines and this forms a greater portion of the previously mined areas as this constitutes ninety one percent of the undermined areas (Canbulat and Ryder, 2002). Since sinkholes seem to occur sporadically, there is need to take reasonable steps to improve sinkhole prediction with a view to pre-identify when and where such events will transpire. This requires understanding of the mechanisms by which the sinkholes form and the conditions that must prevail in order to induce this form of subsidence. Although several studies have been conducted regarding sinkhole subsidence in the western United States (Dyne, 1998), very little research has been done concerning this topic in the South African coal mining environment. As of yet, there are no accurate means available to predict sinkhole formation occurrences above abandoned coal bord and pillar operations. Therefore, it is prudent to always expect the chimney subsidence effect to occur anywhere where previously underground bord and pillar working areas exist unless it can be proven that the area is not undermined, that long-term pillar support is in place, or that the pillars have been fully collapsed (Gray and Bruhn, 1982).

Sinkholes are a peculiar feature in Anglo American coal operations underground mined areas that are overlain by shallow overburden material and have since resulted in a fatal injury thus putting the company safety record into jeopardy. This observed assertion is further supported by the work conducted by Gray et al (1977) which also pinpoints sinkholes as the most prevalent subsidence feature associated with abandoned mined out areas. A sinkhole is caused by the collapse of the mine roof that works its way upwards. These features are steep-sided pits with depth in excess of 0.91m and if not arrested during the formation process; will eventually reach the surface posing risk to both personnel and equipment. This process is governed by the thickness and character of the overburden as well as the width and height of the mine voids.

1.2 **Problem statement and motivation**

In order to maximise coal extraction, Anglo American Coal South Africa is involved in the surface reclamation of pillars in areas previously mined by underground workings. During the pillar reclamation process there is possibility of personnel and equipment exposure to voids or sinkholes from roof collapses of underlying workings or residual sinkholes caused by blasting activities. Exposure to these voids or sinkholes can result in serious injuries or equipment damage. In order to mitigate this risk it was important for Anglo Coal South

Africa to devise a robust sinkhole management process aligned to its "Zero Harm" policy. This will ensure the utmost safety for both personnel and equipment. Concerted efforts were then directed towards establishment of the sinkhole risk management system to formulate a rigorous system to comprehensively identify the areas having potential for sinkholes formation and thereafter take precautionary measures to eliminate the risk associated with these sinkholes.

1.3 Significance of the research report

The sinkhole prediction methodology developed in this research report is being utilised as tool to identify areas amenable to sinkhole formation. These areas with a sinkhole risk are then roughened up to make them safe prior to commencing mining operations. The tool identifies areas within the three year mining window and divides them into high and low risk sink hole prone areas. High risk areas are prone to sinkhole formation and are demarcated as red on the mine plans. Mines used to apply different methods to deal with sinkhole issues, which included, visual inspection, hazard plans and other empirical site based methods, with limited research undertaken. The methodology for sinkhole prediction adopted in this research report proactively identifies areas of potential sinkhole formation way ahead of mining thus leading to a proactive formulation of controls to mitigate the loss of life and equipment in identified potential risk areas. This system is robust and correlates very well with the actual sinkholes formation in the field.

The mine planning and coal extraction has benefited from the sinkhole prediction tool as this has significantly improved the safety of personnel and equipment as well as reducing production stoppages due to machinery falling into sinkholes requiring to be retrieved.

A database has been created to capture all sinkholes occurrences and this facilitates interrogation that assists in back analysis to improve on the integrity of the prediction model and this facilitates derivation of the patterns that may allow one to extract unique traits for further refinement of the current developed model.

1.4 Objectives of the research report

Personnel and equipment safety is the key focus area central to this study and as such the main objective of this work is the development of a comprehensive risk assessment with a view to evaluating the possibility of sinkholes or subsurface cavities occurring at all mines with previously mined underground workings. This process culminated in the development of a comprehensive sinkhole database of all areas affected by sinkholes or cavities followed by the development of a robust sinkhole risk management system aimed at eliminating the risk posed by sinkholes or sub cavities at all Anglo American coal operations inclusive of its managed subsidiaries. The main objective of this research is to:

- Development of a sinkhole management tool to ensure safe coaling in previously mined bord and pillar workings.

1.5 Research methodology

The research is structured in the following manner:

- Gathering mine geometry and geological data for the case study area
- Develop an automated desktop "Sinkhole Prediction Model".
- Develop sinkhole hazard plan to assist in sinkhole management
- Develop risk mitigation measures aimed at reducing the impact of sinkholes.
- Correlate the actual sinkhole occurrence to prediction model and reconcile to enhance method robustness and reliance.
- Pursue other sinkhole prediction methods to improve on current system.

1.6 Structure of the research report

In addition to this chapter, there are four other chapters. This chapter introduces the nature of the problem being discussed and covers the concept of sinkhole development methodology and treatment aspects associated with the coal mining environment in general.

Chapter 2 presents a literature survey of background information and concepts relevant to this research report. It starts by giving further details about the context of the problem. Then it expands on the significance of the research report. Finally, it discusses the technologies available to solve the problem.

Chapters 3 discusses the results of the work undertaken in this research report. It details the development and basis of the adopted sinkhole prediction model and the outcome inclusive of the strength and weaknesses of this prediction methodology. It also looks at other sinkhole prediction methods that were pursued as well as highlight the reasons for discounting them.

Chapter 4 discusses the case study of the adopted sinkhole treatment / rehabilitation methodologies inclusive of further research to optimise rehabilitation

Chapter 5 provides the conclusions and recommendations of this research report.

1.7 **Summary**

The purpose of this chapter was to discuss the background, the main research question, motivation and structure of the research report. The next chapter introduces the literature survey on sinkholes focusing on areas that are pertinent to this research report.

2 LITERATURE REVIEW

2.1 Introduction

There are two main forms of subsidence namely trough and sinkhole. Trough subsidence or sag is defined as a shallow depression on the earth's surface covering an extensive area and is associated with deeper mining and longwalling (Peng, 1978, 1992). This type of subsidence will not be discussed in this report as there is well documented literature to mitigate the surface risks associated with this type of problem (Blodgett and Kuipers, 2002). Sinkhole subsidence which is the main objective of this research report is the most common form of surface subsidence associated with shallow coal bord and pillar mining and is characterised by deep steep sided pits due to progressive roof failure (Hunt, 1980). This sinkhole formation process can also be exacerbated or worsened by poor blasting activities. Poorly blasted overburden in previously underground mined areas during surface mining can lead to residual sinkhole formation which can increase the risk of personnel and equipment falling into the underground mined voids or workings during pillar reclamation as in the case of coal mines in the Witbank Coalfield. According to Hill (1996) sinkhole formation in shallow bord and pillar locations in the South African Collieries is a direct result of the collapse of bord intersection and its progression to surface. Figure 2-1 and Figure 2-2 indicate the cross section and plan view of a normal bord and pillar respectively where H is the depth to floor of the workings h is the mining height, W is the pillar width and C is the pillar centre to centre distance. This phenomenon is generally confined to shallow depth less than 40 m in the South African coal mining environment. Hill (1996) further stated that the formation of sinkholes is not a common feature where overburden thickness is in excess of 40 m for the South African coal environment.

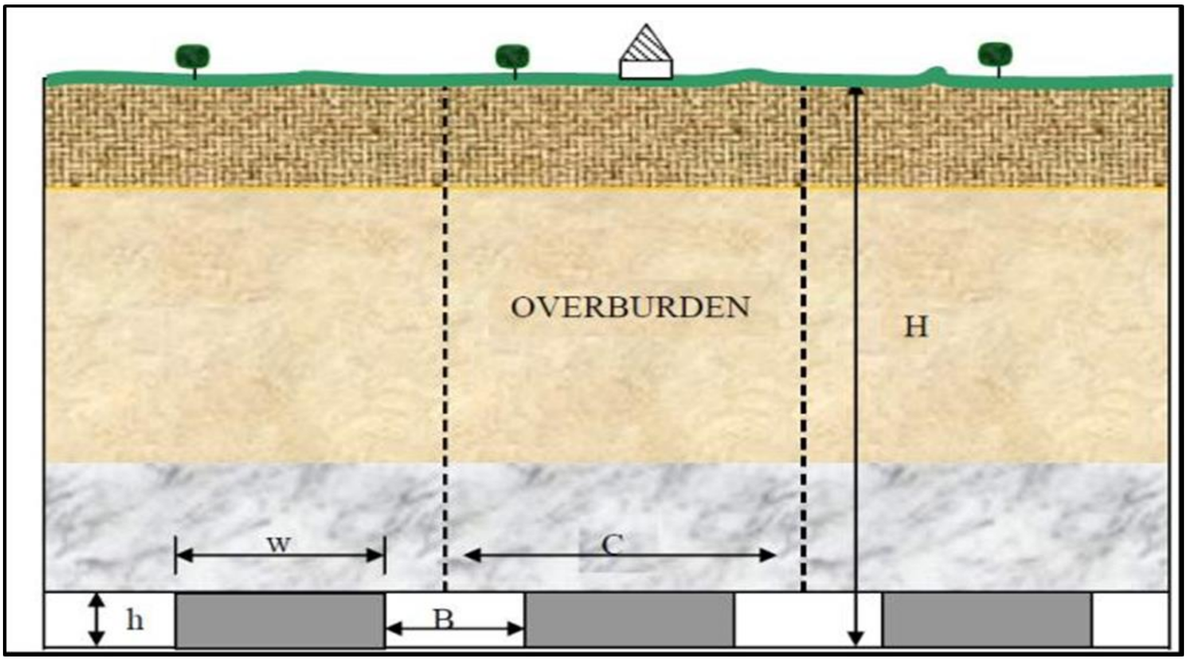

Figure 2-1: Section indicating the bord and pillar mining system.

Van der Merwe (1997), in his work conducted for Vierfontein Colliery concluded that sinkhole formation is the most predominant post mining effect at shallow depth less than 40 m with no expected pillar failure. Van der Merwe (1998b) ascribes the fundamental reason for stable pillars at shallow depth to be a marked reduction in pillar load resulting from frequent roof collapses. This reduction in pillar load after the roof collapses sheds the load on the pillar thus rendering the pillar to be almost indestructible.

According to Gray et al (1977) the most predominant subsidence feature over abandoned mined out land is sinkholes with depth of more than 0.91 m. Sinkhole subsidence usually occurs over abandoned mine workings less than 50 m deep (Hunt, 1980) as indicated by his analysis of the twenty sinkholes in the Jamuna and Kotma area of South Eastern Coalfields Limited (SECL) in India. This work indicated that the majority of sinkholes occurred between a depth ranges of between 15 and 35m. Hunt's sinkholes depth range contradicts the Hill (1996) sinkhole formation upper limit depth range of 40m for South African collieries in the Witbank area and this can possibly be attributed to different overburden behaviour for the different mining environments, thus indicating the need to use site specific sinkhole formation data as a basis for prediction formulation.

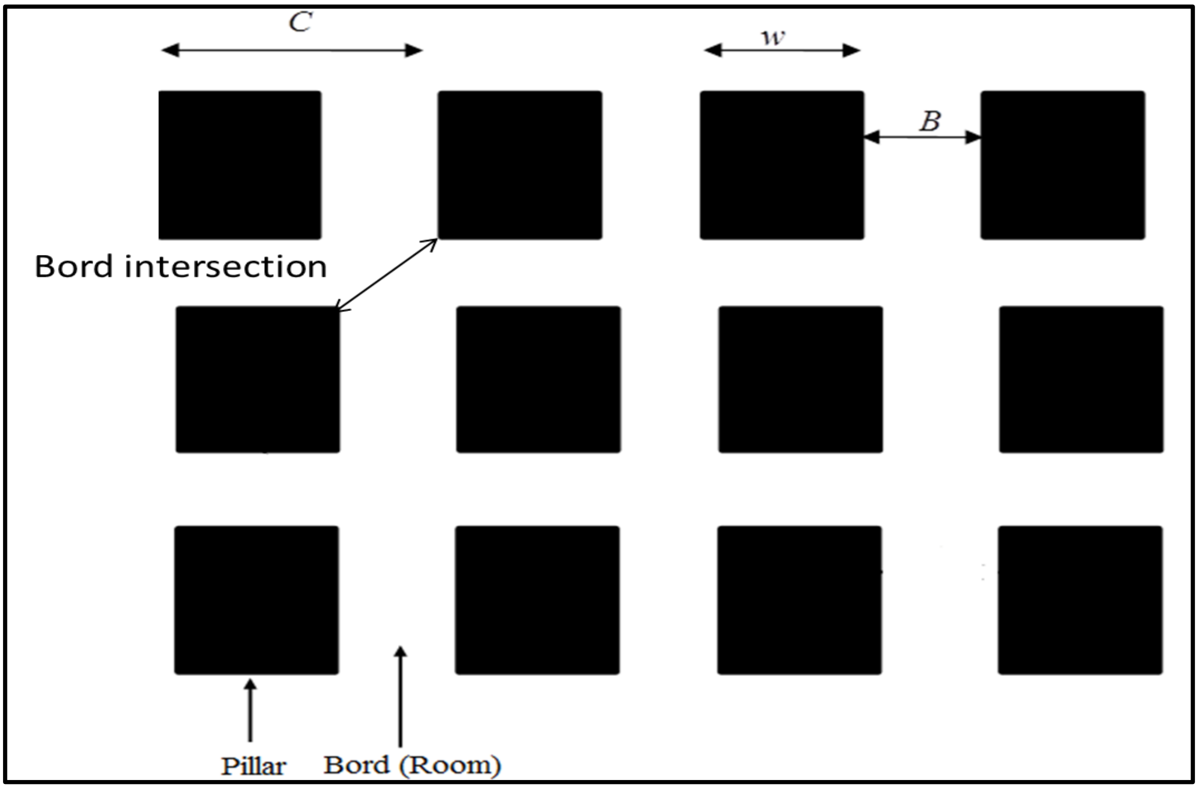

Figure 2-2: Plan view indicating the bord and pillar mining system modified after Van der Merwe 2011.

The need for the development of site specific sinkhole prediction methods is also further supported by Matheson and Eckert-Cliff (1986) found that chimney type sinkholes are likely to occur when the overburden thickness to mining height ratio is less than 4 to 5, with a rapid decrease in potential formation as the ratio increases to in excess of 5. This observed phenomena regarding sinkhole occurrence environment and characteristics is similar to the South African Collieries observed trends, thus confirming the accuracy of the local formation characteristics at Mine X.

Figure 2-1 indicates the variable depth of sinkhole occurrences for the different mining environments.

.

Table 2-1: Mining depth for case in which sinkholes subsidence is reported (After Kalendra et al, 1997)

SI.No	Location	Reference	Maximum depth (m)
1	Western Pennsylvania	Gray et al, (1978)	47.7
2	Hanna Area, Wyoming	Berg (1980)	73.2
3	Sheridan Area ,Wyoming	Dunrud and Osterwald (1980)	77
4	Beulan Area ,North Dakota	Dunrud and Osterwald (1980)	24.4
5	Illinois Coal Basin	Hunt (1980)	50.3
6	St David Area, Illinois	Wildanger et al. (1980)	50.3
7	Colorado Springs Area	Matheson and Pearson (1985)	45.7
8	Superior ,Wyoming	Brown (1986)	30.5
9	Rock Springs ,Wyoming	Colaizzi (1986)	101.5
10	Glenrock , Wyoming	Gormely (1986)	30.5
11	Handidhua and Deulbera Mines	Singh (1986)	40
12	Humberside and Lincolnshire	Whittaker and Reddish (1989)	90
13	Mithapur Colliery ,India	Anon. (1994)	25
14	Jamuna and Kotma area ,India	Singh and Dhar (1996)	43

Sinkhole formation is principally associated with roof failure. These surface expressions characteristically referred to as pit or sinkholes or pothole subsidence are a common form of surface expression associated with shallow bord and pillar mine workings.

Figure 2-3 and Figure 2-4 shows the actual chimney type caves prior to rehabilitation on one of the case study sites within Anglo American Coal Division (AACD) operations. Sinkhole formation is associated with the collapse of the mine roof bord or intersection. These bord intersections represent locations with the largest extent of exposed roof. This leads to the high induced stresses in the immediate roof beds or supericumbent strata (Whittaker and Reddish, 1989).

The propagation of the bord collapse to surface can be arrested prior to reaching the surface if a competent beam or layer is encountered in the overburden or supericumbent material overlying the mined out void or workings. The progression of void formation can also be stopped by self-choking and natural bulking of the caved rock. This movement (void migration) can also be arrested by the formation of a new, stable self-supporting beam (Whittaker and Reddish, 1989; Karfakis, 1986). If however, there is a shallow depth cover or the overlying stratum is weak or wet, the caved material might flow into the mine void along the chimney causing caving to reach surface.

The presence of wet unconsolidated strata can result in “slurry” running into the mine void giving rise to large pothole forms of subsidence (Misich et al, 1993). Tension cracks or fractures created by mining or pre-existing in the overburden may serve as planes of weakness assisting caving. Pit subsidence is frequently much deeper than the thickness of the coal seam (mining height), thus contradicting the theory that swelling of the caved material will limit subsidence to some fraction of the extracted seam thickness (mining height). This disparity is often attributable to the flow of caved material throughout the mine due to water wash out. Mining depth is the most influential determining factor for whether subsidence event would be pit or trough type.

According to Piggott and Eynon (1978) sinkhole caving normally propagates to 3 to 5 times the height of the excavated seam with a maximum height attained being up to 10 times the height of the excavated seam. After conducting a study of a coal mine subsidence in Wyoming (Dunrud and Osterwald, 1980) confirmed the upper limit of sinkhole development interval suggested by Piggott and Eynon (1978) which is a caving height of 10 times the excavated seam height. The data correlated well with Piggott and Eynon's established upper limit except for cases where the caved material would have moved laterally.

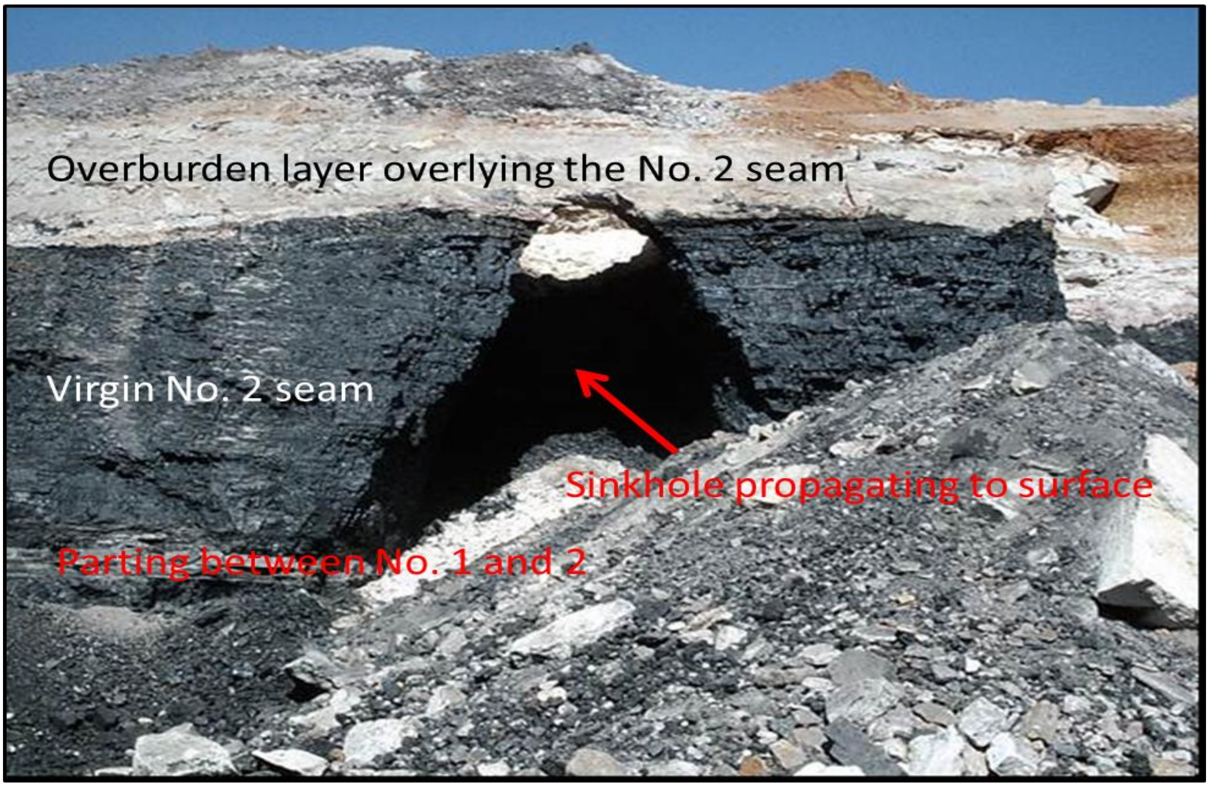

Figure 2-3: Sinkhole progressing to surface through the No 2 coal seam.

This is a result of material flowing through the existing or fresh made cracks in the overburden into the adjacent mine entries or voids. In western Pennsylvania, most sinkholes develop through cover depth less than 15 m (Bruhn et al, 1978).

Figure 2-4: Progressive failure of the roof and sinkhole migration to surface.

The risk emanating from sinkhole formation can result in a compromised safety of the mining environment. Anglo American Coal has always had a sinkhole risk management system put in place to safeguard personnel and equipment. Despite the existence of this diligent sinkhole risk management system an unfortunate serious incident occurred that resulted in a person falling into a sinkhole, leading to a loss of life. Subsequent to the occurrence of the serious incident, the need arose to remodel the entire sinkhole management system using the known database of occurring sinkholes. This was a calibration exercise meant to enhance the robustness of the sinkhole management system for the safety of personnel and equipment. Prior to the incident occurrence the sinkhole prediction model was based on the hazard index model which is a function of the ratio of hard overburden material to total overburden overlying the previously underground mined workings or seam. This culminated in the computation of a hazard index that formed the basis for delineation of different zones into high, medium and low risk within the mining area. These areas were colour coded into different schemes signifying the risk level associated with each mining zone or block. The different zones were then incorporated into the total mine plan thus forming a sinkhole hazard management plan aimed at guiding the required treatment to facilitate safe coal extraction. The hazard index is calculated as follows:

$$Hazard\ Index = 10 - 9 * \frac{(Hards\ overburden\ thickness)}{(Total\ overburden\ thickness)} \qquad \text{(4) Hill (1996).}$$

The risk associated with different mining zones is then categorized as follows:

Table 2-2: Sinkhole potential classification associated with mining blocks or zones (After Hill, 1996).

Hazard Index	Risk category or Level
0-5	Low
05-Aug	Medium
>8	High

This hazard index had a high correlation with the majority of the actual sinkhole incidences that had occurred in undermined shallow workings (Hill, 1996).This sinkhole risk prediction model, however tends to underestimate sinkhole occurrence for shallow mining conditions and also has an overestimation effect for deeper mining environments. This inherent under or over estimation according to Hill (1996) is a direct consequence of the effect of the span / depth ratio which has been shown to influence sinkhole development. It has been recommended by Hill (1996) that caution should be exercised in the usage of the hazard index criteria for conditions where the thickness of the hards material in the overburden is below 5m.

2.2 Mechanisms of sinkhole formation

The most probable mechanism of sinkhole development is the progressive collapse of the immediate supericumbent strata overlying the previously mined and abandoned mine opening.

During the coal extraction process, the overburden load previously supported by the solid coal seam is transferred to the pillars left in situ. This state results in high stresses in the supericumbent strata directly lying above the mined void. According to Karfakis (1986), the tensile stresses in the immediate roof layers and or high compressive stresses in the upper corners of the mined out void may develop depending on the initial state of stress. In the presence of the vertical fractures or joints, the tensile stress will not develop, however creation of fractures may occur. The roof deflection downwards could lead to the formation of a self-supporting arch or Voussoir beam. Compressive stresses will develop on the upper corners of the resulting voussoir arch as well as the abutments. Any changes in the stress regime due to pillar and roof deterioration over time can lead to unstable roof, if the stress changes exceed the roof strength. Karfakis (1986) indicated that changes in stress or strength due to ground water fluctuations, creep, blast and mechanical vibrations may lead to instability of the roof overlying the mined out void. The presence of water may deteriorate the rock strength. Rock strength can also be impacted by fluctuation in hydrostatic head and pore water pressure with the rockmass. This variation in the relative humidity and weathering of unstable minerals can cause slaking. According to Karfakis (1986) there are two basic models by which the overburden can fail namely:

- Shear and
- Flexural(Tensile)

Assuming the rockmass behaves like a continuous beam, it will fail in following:

Shear if

- High horizontal as well as vertical stresses exist
- Pillars are stiffer than the roof
- Softer layers overlying the immediate roof exist
- Shear strength of roof rock is exceeded by the shear strength of the pillar side abutment

Flexural (Tensile) if

- The loading is in the vertical plane
- Low ratio of horizontal to vertical stress exists
- Thinly bedded or supported roof layers exist and

- Bending generates tensile stresses which exceed the tensile strength of the rock

The possibility of pillar crushing if the uniaxial compression strength of the beam is exceeded by the load of the overburden material is also a possibility as indicated in Figure 2-5.

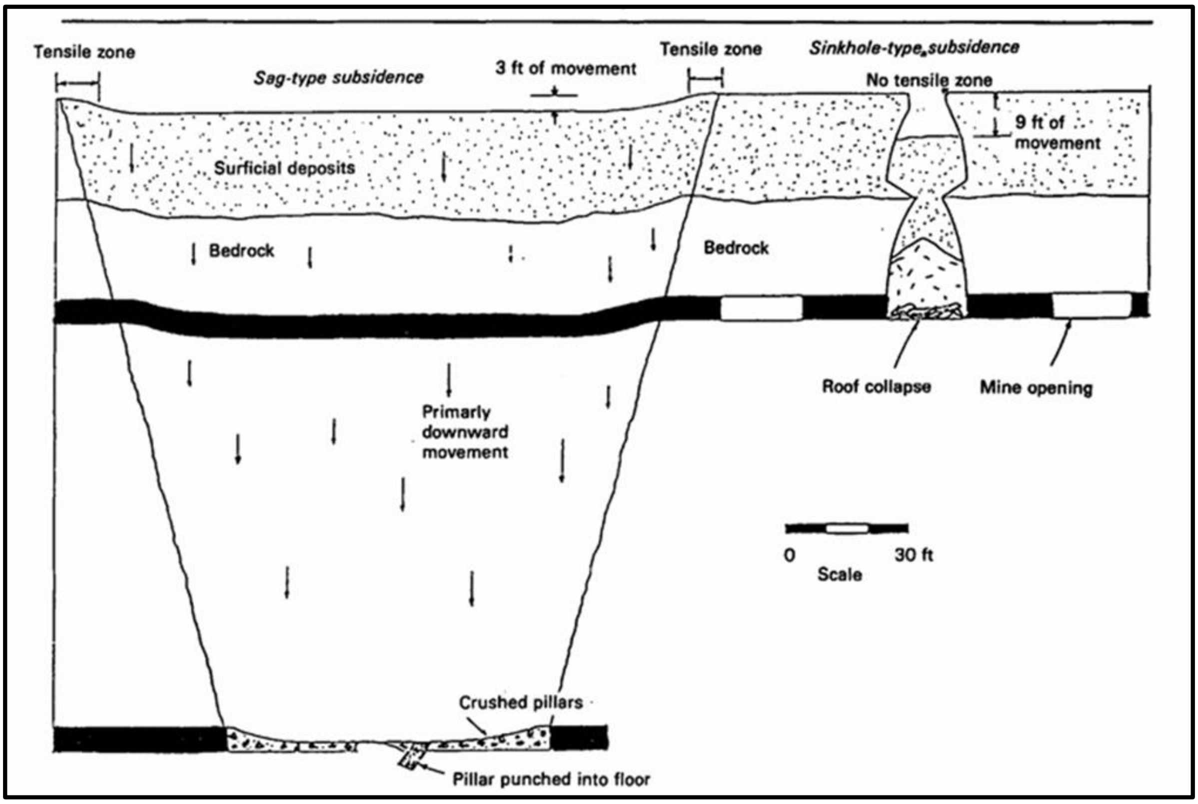

Figure 2-5: Sectional view indicating the position of tensile and compressive failure.

2.3 **Causes of sinkhole subsidence**

The most probable causes of sinkhole development associated with shallow bord and pillar mining are as follows:

2.3.1 Incremental failure of the roof to surface (roof failure)

According to Van der Merwe (1997) this is caused by the progressive upward weathering and failure of the roof strata until the weak weathered zone from surface is intersected. Where failure mechanism is governed by the tensile strength of the strata, intersection failures and sinkholes are likely to occur than roadway collapse due to onset of higher tensile stress in the intersection compared to the bord. This is attributable to the height of collapse above an intersection being higher, since the fallen material can spill into the roadways (Van der Merwe, 1998b). Where the failure is controlled by shear strength of the overburden, roadway failure and trough subsidence takes place. Incremental failure can be arrested by bulking of the caved material thus preventing further failure from occurring (Van der Merwe, 2002). A proportion of the failed material thus spills into the roadways forming and angle of repose (Canbulat and Ryder 2002). Depth of mining is also an important limiting factor for this mechanism since the tensile zone tends to decrease with mining depth (Karfakis, 1986).

2.3.2 Shear / tensile failure of the immediate roof due to overburden weight

This type of failure is characterized by weight of the weak overburden causing shear or tensile failure of the immediate mine roof. The important factor is the depth of weathering and thickness and strength of the immediate roof. This type of failure has a depth range of occurrence of less than 40 m due to the effect of span / depth ratio (Brady and Brown, 1993).

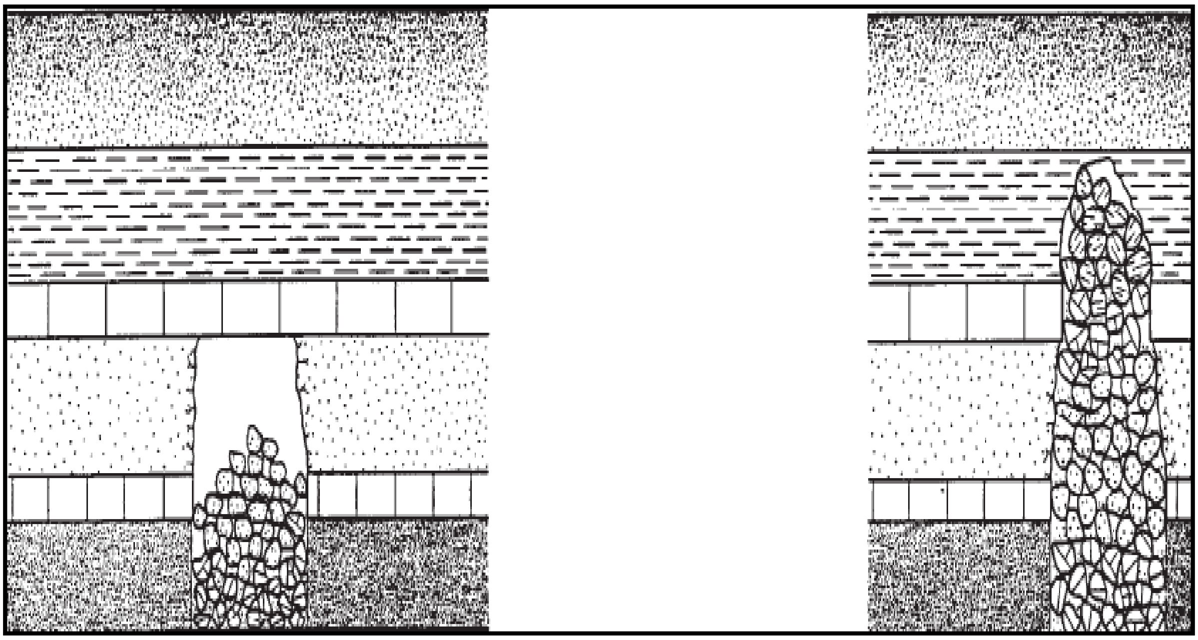

Figure 2-6: Formation of chimney above mine workings (Brady and Brown, 2003)

2.3.3 Plug failure- (Brady and Brown, 1993)

This type of failure is characterized by sliding of the whole overburden along structural feature contacts due to insufficient resisting force of the surrounding rockmass as indicated in Figure 2-7. For sinkhole development a weak overburden with vertical discontinuities has to be present (Brady and Brown, 1993). There are no known records of sinkholes emanating from this type failure mechanism in South Africa.

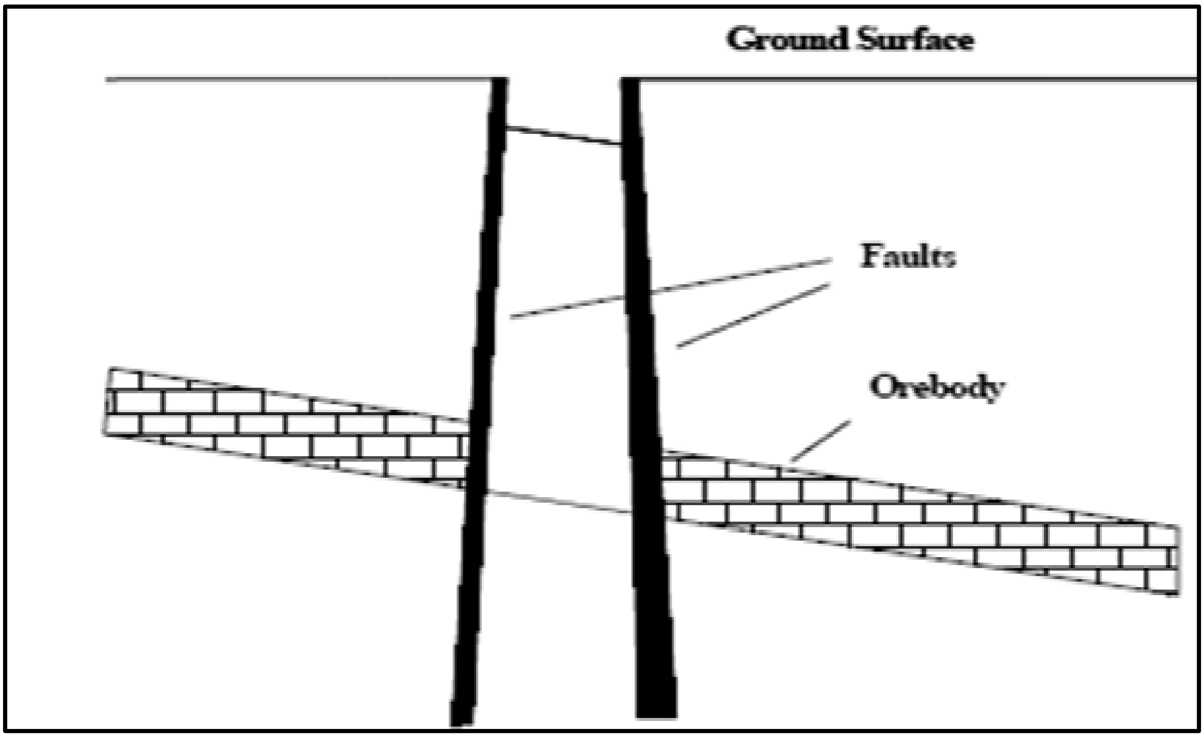

Figure 2-7: Plug subsidence **(**Brady and Brown**,** 2003**)**

2.4 **Sinkhole prediction methodology**

Most of the proposed sinkhole prediction theories apply only to active coal mines (Whittaker and Reddish, 1989). Various theories predict the roof stability of mine openings and this applies to sinkholes formation as it also is a roof stability problem in most instances (Whittaker and Reddish, 1989). These theories require detailed information regarding the mine geometry and geology, which information is readily available for operational / working mines. However in the case of abandoned mines, subsurface conditions are difficult to obtain (Gray and Bruhn, 1982). The problem of predicting sinkhole formation resulting from the collapse of underground voids has in the past, generally been approached using empirical and semi empirical approaches (Dyne, 1998). An attempt to use finite element and limit equilibrium analysis has been challenged with the need to incorporate associated flow rules aimed at establishing rigorous bounds on true collapse loads for many problems in geomechanics that are not unduly kinematically constrained (Whittaker and Reddish, 1989).

The introduction of finite element limit equilibrium analysis methods has significantly managed to improve a few analytical (non-numerical solutions) but the most favourable and feasible solution seems to be in favour of site specific data analysis (Whittaker and Reddish, 1989). The theory for computing the mining height of the cavity of the collapse or sinkhole above the room intersection was proposed by (Whittaker and Reddish, 1989). This theory utilises the rooms' geometry, bulking factor of the caved material and the angle of repose of the caved rock to predict the height of the collapse chimney / sinkhole. Similar approaches have also been proposed by (Price et al 1969, Piggott and Eynon, 1978 and Dunrud, 1984). These proposals gave rise to simplistic relationships between height of the collapse or sinkhole, thickness of extracted material (mining height) and the swell factor of the roof material. This simplistic relationship resulted in an empirically developed formula to predict if caving could reach surface before self-choking (Whittaker and Reddish, 1989). The disadvantage of this geometrical analysis is that it is idealistic as it assumes constant bulking factor, with no lateral movement of the rubble and perfect geometry (Whittaker and Reddish, 1989). It thus seems that the most accurate means of predicting sinkhole subsidence is to examine the sites where it has already occurred.

In an attempt to develop a robust sinkhole prediction model for a case study operation in Anglo American Coal, a combination of analytical geometrical analysis methods were utilised. These common methods according to Canbulat and Ryder (2002) are not limited to beam theory (tensile and shear stresses) and bulking factor analysis. These were used in developing a predictive model to assist in the identification of blocks or mining zones amenable to sinkhole development (Canbulat and Ryder, 2002). The simple reason for adopting this was due to the fact that sinkhole development will be initiated by failure of the immediate layer and this failure is either tensile or shear. It often happens that that if the tensile strength of the material is not high enough, it will fail and initiate the process of sinkhole development and the broken material will spill into bords (Canbulat and Ryder, 2002). The amount of material that spills into the bords will be determined by the bulking factor, mining height and bord width. The immediate layer may fail and the material will spill into the bords (Canbulat and Ryder, 2002). The fundamental principle underlying sinkhole development is the determination of whether the immediate roof or layer will fail or not and to ascertain if the dimensions are large enough to allow sufficient material into the workings for failure to intersect or reach the surface (Canbulat and Ryder, 2002).

2.4.1 Tensile stress analysis

This method considers the tensile strength of the immediate roof rock and ascertains whether failure will happen or not. The procedure to predict failure entails determining if the tensile stresses are within the limits the material can sustain without initiating failure (Obert and Duvall, 1976). The safety factor is the ratio of the tensile strength to the tensile stress (Obert and Duvall, 1976). For long term stability safety factors of 6 and 8 were suggested for roadways and intersections by (Obert and Duvall, 1976). Considerations should be given to additional loading emanating from thinner overlying strata and also deadweight loading from totally weathered material. Under wet conditions a differential water pressure will exist on the immediate roof (Canbulat and Ryder, 2002). The tensile stress due to additional deadweight loading can be calculated from:

$$\sigma_t = \left(\frac{\gamma_s t_s + \gamma_u t_u}{2 * {t_s}^2}\right) * b^2 \qquad (1)$$

Where:

γ_s-density of the immediate competent layer above coal (MN/m^3)

γ_u –density of overburden (MN/m^3)

t_s-total thickness of competent layer above coal (m)

t_u-total thickness of weathered material or depth below surface (m)

b-span (intersection diagonal width) (m)

σ_t-tensile stress in (MPa)

Figure 2-8 and Figure 2-9 are schematic sketches explaining the various terms associated with equation 1 and 2.

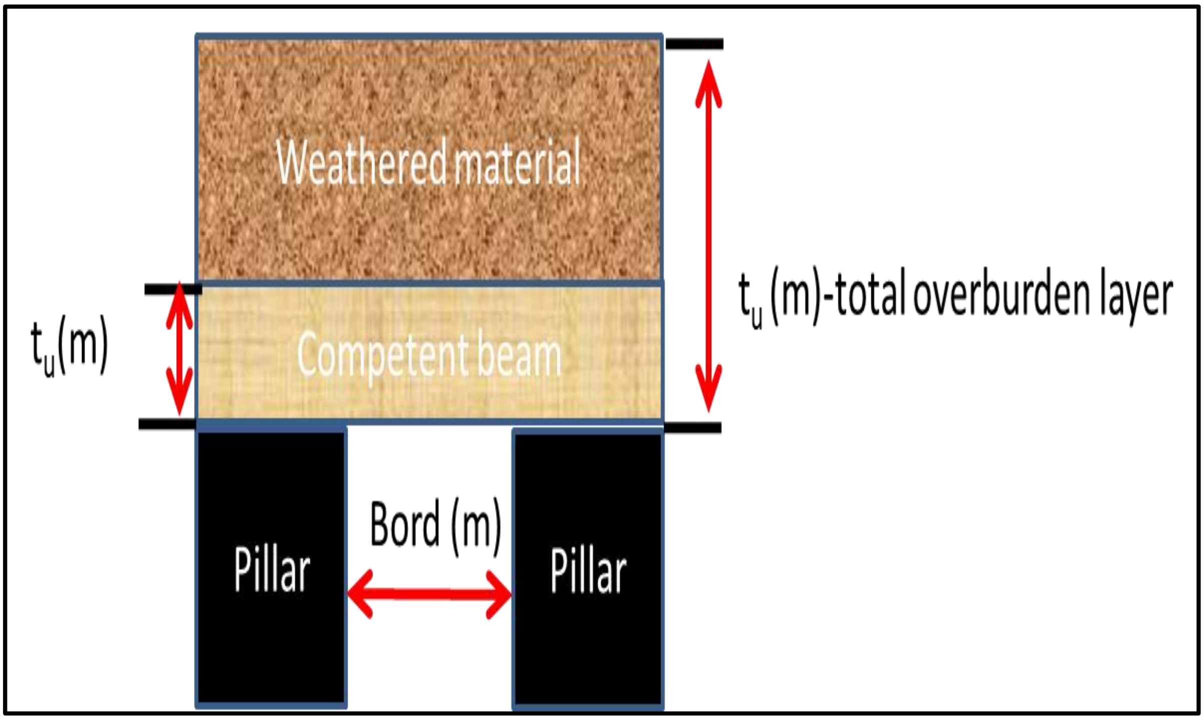

Figure 2-8: Schematic sketch indicating the geometrical terms in equation 1

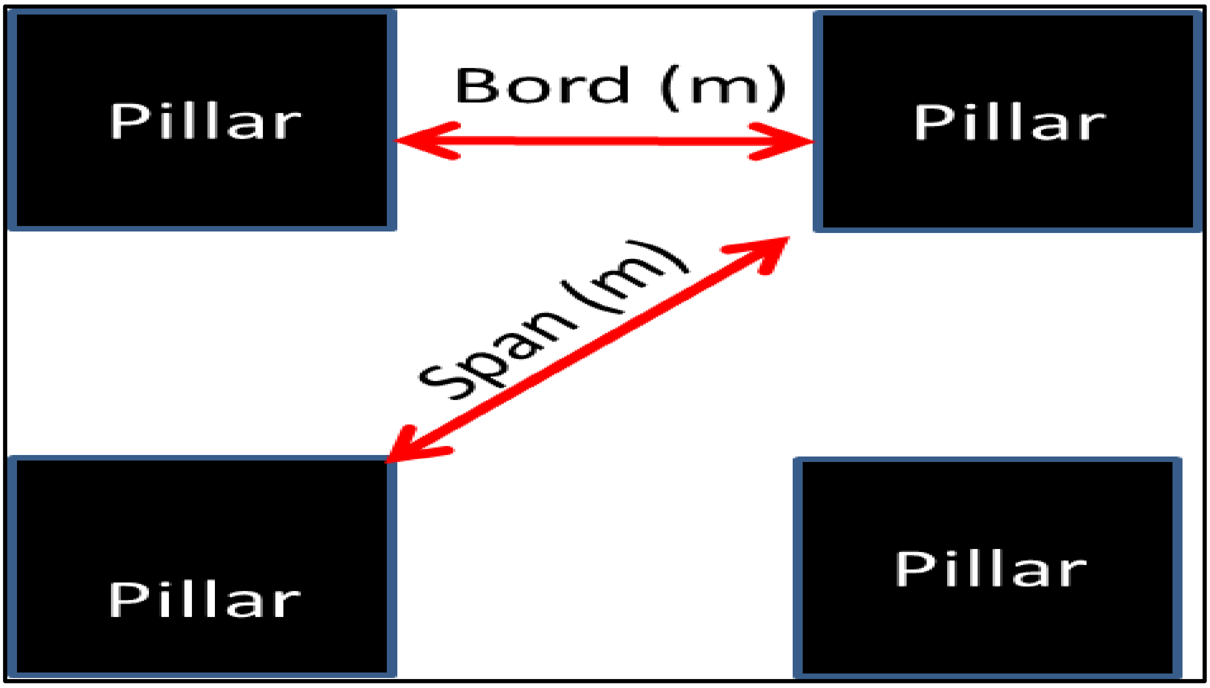

Figure 2-9: Plan view indicating the intersection span in a bord and pillar environment.

Making t_s the subject of the formula, the critical thickness of the competent layer can be ascertained. Critical span b can be determined and compared with the mining spans as determined from the mine plans.

2.4.2 Shear stress analysis

The immediate layer can also fail in shear. This occurs when the shear stress in the immediate layer exceeds the shear strength. The shear stress can be calculated as follows:

$$\tau_t = \frac{3(\gamma_s t_s + \gamma_u t_u)\mathrm{b}}{4t_s} \qquad (2)$$

Where:

τ_t-shear stress (MPa)

2.4.3 Bulking factor analysis

Bulking factor refers to the ratio of the total volume (solid plus voids) to solid volume. Collapse migration will halt when the fallen material fills the void through bulking. For an intersection collapse which represents the worst case scenario the height of caving can be determined from the following formula:

$$z = \frac{4(2bh^2 cot\emptyset + hb^2)}{(k-1)\pi d^2} \qquad (3)$$

Where:

z=height of collapsed chimney

k=bulking factor (typically 1.3)

d=diameter of collapsed chimney ($b\sqrt{2}$)

h=excavation height

b=bord width

ϕ=angle of repose (typically 35º).

Figure 2-10 is a schematic sketch explaining the various parameters in the caving height formula.

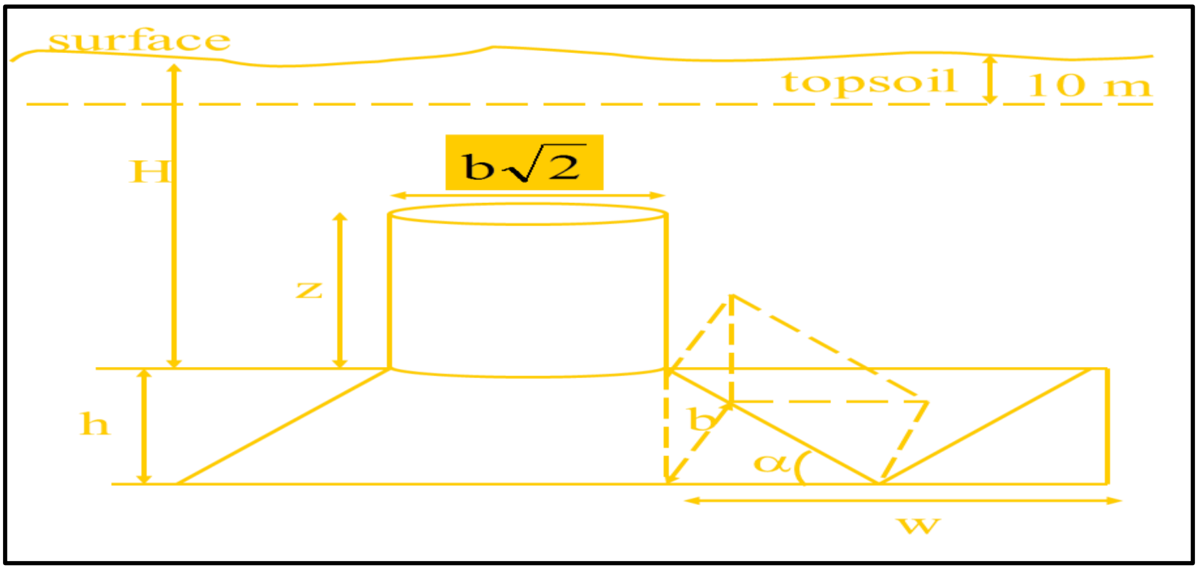

Figure 2-10: Schematic sketch indicating the various parameters of the caving height (Canbulat and Ryder, 2002)

The height of caving reduces with increased bord width as indicated in Figure 2-11 due to the proportionately small amount of material spill into the roadways. The height of collapse for a roadway is less than for an intersection since more material will spill out into both roadways.

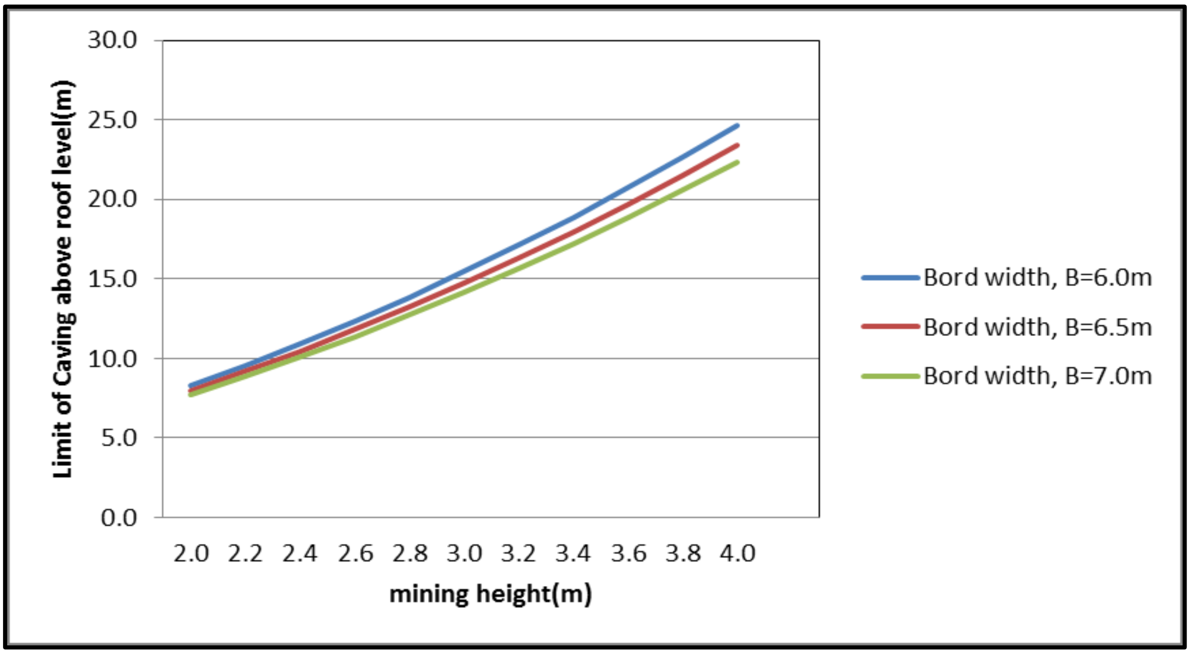

Figure 2-11: Variation of Caving height with increased bord width and Mining height (Hill, 1996.

2.5 **Factors influencing Sinkhole formation**

Chimney or sinkhole subsidence is limited to shallow mining depth ranges less than 40m with elevated sinkhole / chimney formation taking place at depth less than 15m (Hill, 1996).

- Strata type-failure is more likely to take place in weak and thinly laminated strata, strata that weathers rapidly and these are characterized by less than 30% sandstone.
- Bord width-failure is more likely to occur in areas with large spans.
- Extraction height-does not influence initial failure but determine the height of caving before bulking arrests upward migration.
- Vibrations due to equipment -may cause failure of roof which is further exacerbated by the exertion of their weight on the ground underlain by underground workings.
- Blasting activities-induce cavities in blasted ground prior to levelling and coal exposure.
- Water-during percolation into blasted ground causes cavity manifestation.

2.6 **Summary**

This chapter discussed the different forms of subsidence associated with any previously mined workings which are shear and flexural. It identifies the predominant form of subsidence associated with the shallow mining environment at depth shallower than 40m which is the main problem being pursued in this research report. It discussed the sinkhole prediction methodology adopted in this research to identify areas of potential risk as well as identifying the sinkhole aggravating factors. The next chapter discusses the development of the sinkhole prediction methodology that endeavours to identify potentially hazardous areas. Furthermore the refinement and implementation of the sinkhole prediction model is discussed. The chapter concludes by pinpointing the challenges associated with the sinkhole risk mitigation program to prevent loss of life and equipment damage.

The next chapter has four sections. The first section discusses the sinkhole prediction model and its intended purpose. This is followed by the validation of the prediction model using the field sinkhole occurrences. The third section discusses the management of the identified hazardous areas and the fourth section assesses the challenges associated with sinkhole management with a view to mitigate the loss of life and achieve sustainable productive levels.

3 SINKHOLE PREDICTION MODEL DEVELOPMENT

3.1 Chapter overview

This chapter is divided into four sections. The first section discusses the development of the sinkhole prediction model. The second section discusses the sinkhole model prediction validation aimed at ascertaining the robustness of the system and its correlation to the actual sinkhole occurrences. The third section discusses the sinkhole hazard management process inclusive of the rehabilitation to ensure safe coal extraction. The fourth section assesses the challenges associated with the sinkhole management with a view to mitigate the loss of life, equipment damage and save cost to achieve sustainable productivity levels.

3.2 Theoretical "Sinkhole Prediction Model"

3.2.1 Rationale of the "Sinkhole Prediction Model"

Most of the methods used in the prediction of the occurrence of chimney caves are reliant on the geometry of the abandoned mine or previously mined areas to predict the height of caving. As is often the norm, the sinkhole prediction formula in areas suspected to be prone to sinkhole occurrence at site X within the Anglo American Coal operations commenced with pursuit of the existing and well known caving height formula by Hill (1996). Hill (1996) indicated that collapse of any underground void will stop when the fallen material has completely filled the void through bulking. He reckons for an intersection (representing the largest possible opening underground) that the limit of caving can be derived using equation 3. This equation utilizes the bulking factor and angle of repose of the caved material, the width and excavated height of the mine rooms, and the assumed diameter of the collapse-chimney to predict the height of the collapse-chimney. In order to determine whether or not there is a possibility of developing a sinkhole on the surface, one would compare the thickness of the overburden in the area of interest to the calculated height of the collapse-chimney. If the thickness of the overburden were to exceed the height of the collapse-chimney, the hole would not propagate all the way to the earth's surface. The Hill caving height formulae as first discussed by him in 1996 became the fundamental basis for "Sinkhole Prediction Model". The caving height formulae was then modified to match the observed behaviour of sinkholes based on previous occurrences at site X. Analysis of a few sinkhole incidences indicated the elevated risk to personnel and equipment when sinkholes were within 5m from surface. This culminated in the development of a supposedly robust “Sinkhole Prediction Model” that divided the mine blocks of approximately 100m by 60m into Red (High risk) , Yellow (Moderate risk) and Green (Low risk) areas within the mining window.Three criterions were used to determine the possibility of sinkhole formation and all three conditions had to be satisfied and under conditions where there was no satisfaction of the three conditions, the worst case scenario over ruled all other conditions and these are as follows:

- Low risk if (Mining Combined (MC) thickness – No 1 seam (S1) thickness) + Overburden (OVB) thickness – caving height) > 10m and the thickness of hards in the overburden is greater than 5m. This will be colour coded green on the hazard index plan.
- Medium risk if (MC thickness – S1 thickness) + OVB thickness – caving height) < 10m and the thickness of hards in the overburden is < 5.0m and the hazard index plan will be colour coded yellow on the hazard index plan.
- High risk if (MC thickness – S1 thickness) + OVB thickness – caving height) < 5 and the composition of hards in the overburden is < 3m, the hazard index plan should be colour coded red.
- Mining areas within 20m of the seam sub outcrop and below 20m depth of overburden cover were considered automatically high risk and were colour coded red on the hazard index plan.

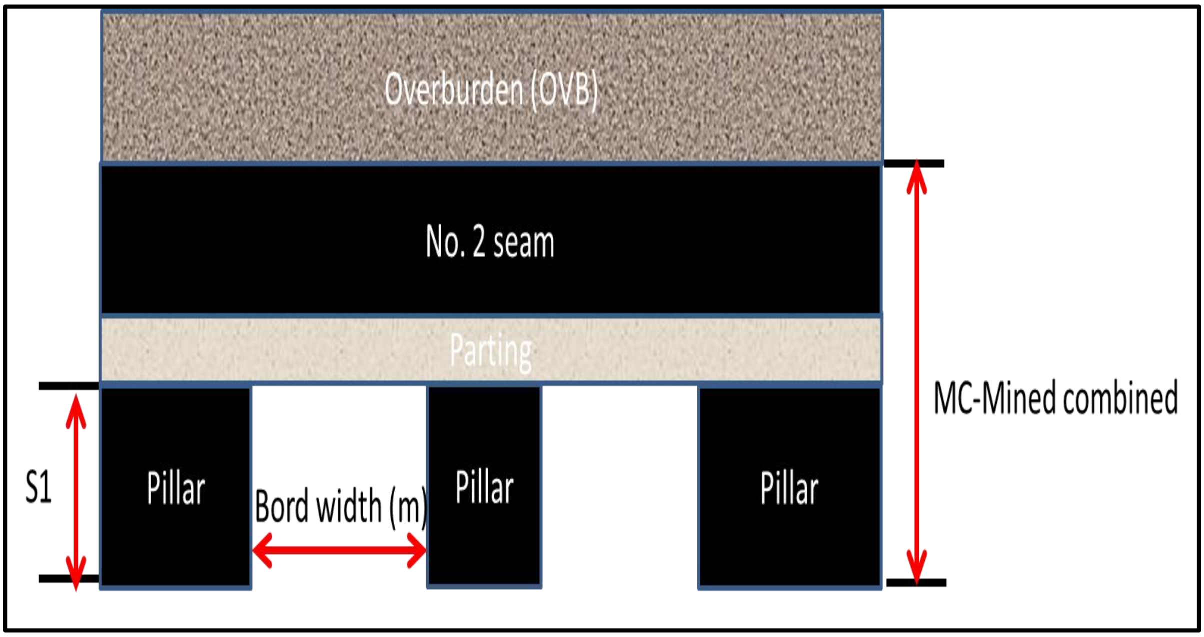

Figure 3-1: Schematic diagram indicating the combined mining horizon (No.1, 2 and parting) and lithological sequences.

The final hazard rating for each block was dictated by the above criteria in conjunction with the following observations such as:

- Vicinity of workings to outcrops, clay runs, structural features and water courses.
- Depth of weathering for each block
- Thickness of competent beam in the overburden
- Existence of pillar robbing in the area
- Degree of over stoping in the area (top and bottom coaling)
- Thickness of parting between No 1 and 2 seam horizons.

The generic risk assessment culminated in a hazard index plan as depicted below:

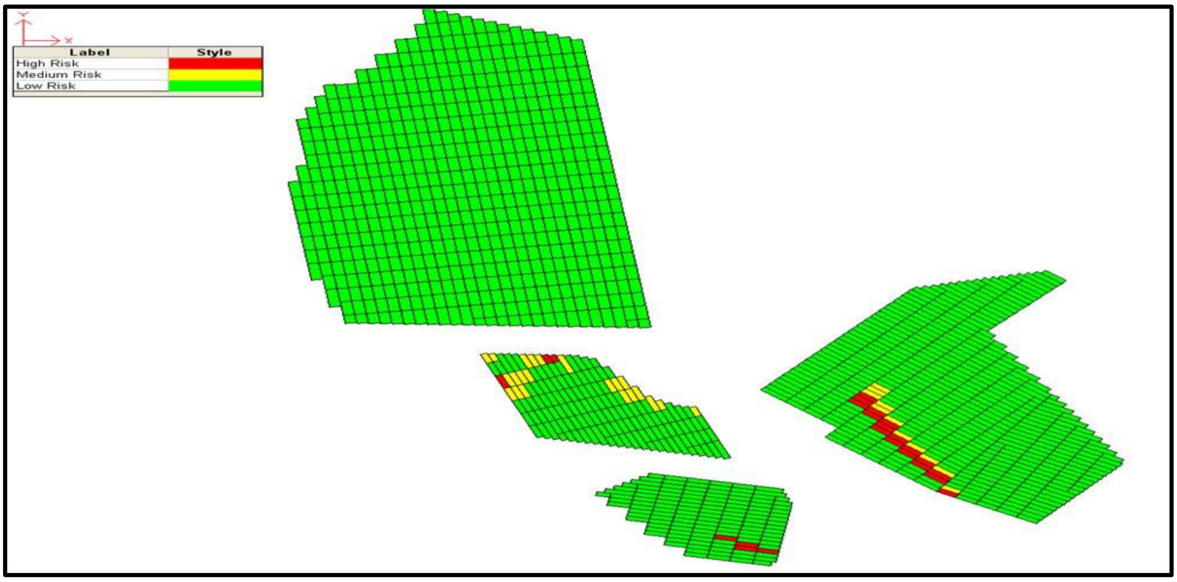

Figure 3-2: Division of the Life of Mine (LOM) area into low, medium and high risk areas based on “Sinkhole Prediction Model” (Klingeberg,2012).

The generic sinkhole prediction model is an automated system making use of an XPAC Command Module (XCM) algorithm that reads information from the mine planning model, which in turn is based on the geological model. The outcome is an automatic subdivision of the Life of Mine (LOM) blocks of 100m by 60m into low (green), medium (yellow) and high (red) risk zones as indicated in Figure 3-2. This has assisted in the timely generation and efficient retrieval of mine hazard plans to facilitate production with no interruption.

3.2.2 Validation of the “Sinkhole Prediction Model”

Following the identification of sinkholes in areas that were not expected there was need to review the entire process. This was brought about due to the following reasons:
The caving height formula by Hill (1996) has the following limitations:

- Overestimates the occurrence of sinkholes in shallow areas (less than 20m cover depth) with hards composition in the overburden less than 5m.
- Underestimates the occurrence of sinkholes at depth cover greater than 20m with hards composition in the overburden less than 5m.
- Underestimates the influence of vibrations due to blasting and equipment.
- Underestimates the effect of lithological composition of the overburden (influence of weak layers / rocks such as shales, siltstone etc.).

- Underestimates the erosion of the failed material by the water at the toe of the failed material.
- Underestimates the continual recharge and discharge of water impacting on the stability of the overburden in direct contact with water above the workings.

To counter act the above, it was necessary to conduct a detailed validation process using the database of fifty four sinkholes with a view to ascertain the sinkhole site specific prediction model. The original database contained fifty four sinkholes incidents, however, upon further examination it was determined that four of the holes had developed under circumstances not due to chimney subsidence but tended to occur after blasting, thus a total of fifty cases were retained for analysis. The rigorous process encompassed the studies of the following characteristics pertaining to the fifty sinkholes:

- Characteristic analysis of sinkholes (depth of cover and lithology types)
- Softs overburden to hards overburden ratio
- Distance of occurrence relative to workings edges
- Physical evidence(water levels, water channels and surface expressions)

The detailed analysis of the above characteristics led to the following fundamental conclusions:

- Sinkholes are highly unlikely to occur in areas with overburden depth greater than 20m as indicated in Figure 3-4 (99 % of sinkholes occurred in overburden depth less than 20 m and average depth of cover of area analysed was 20m).

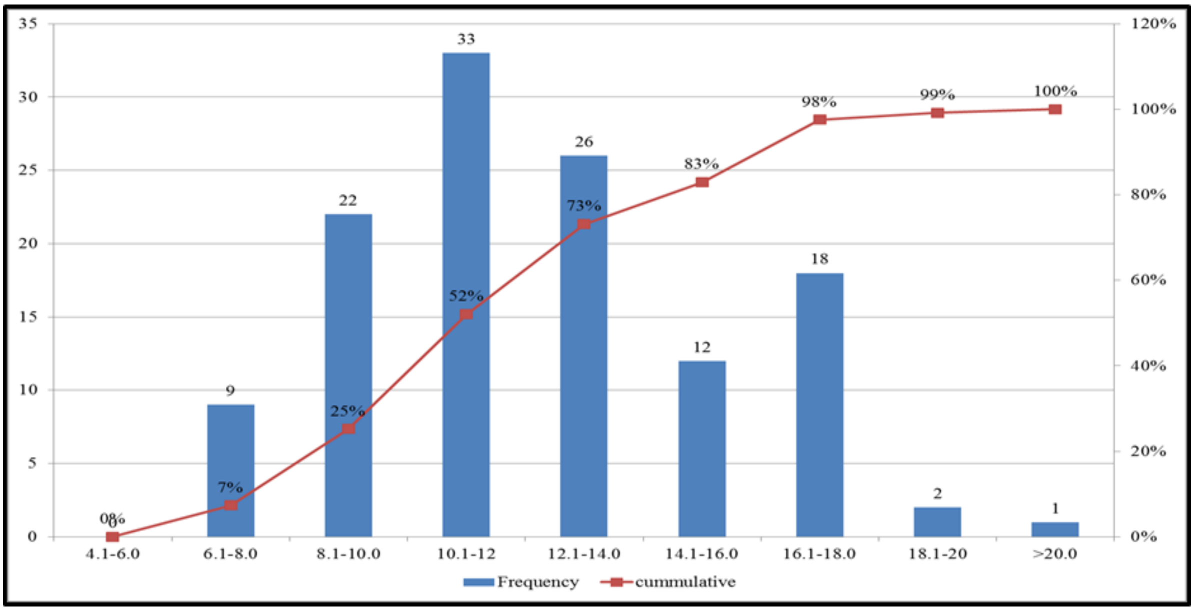

Figure 3-3: Relationship between sinkhole occurrence and overburden thickness.

- The chances of sinkholes occurring in overburden comprised of a beam of greater than 5m hard overburden is quite remote as indicated in Figure 3-5 (90% of sinkholes occurred in hards composition in the overburden less than 5 m and the average thickness of hards in analysed area was 7m). Sinkholes occurring in areas with more than 5 m hards material in the overburden occur after blasting and manifest during the overburden removal by the dragline. These are a direct result of the weight of the machinery which impact on areas that are not fully collapsed during blasting.

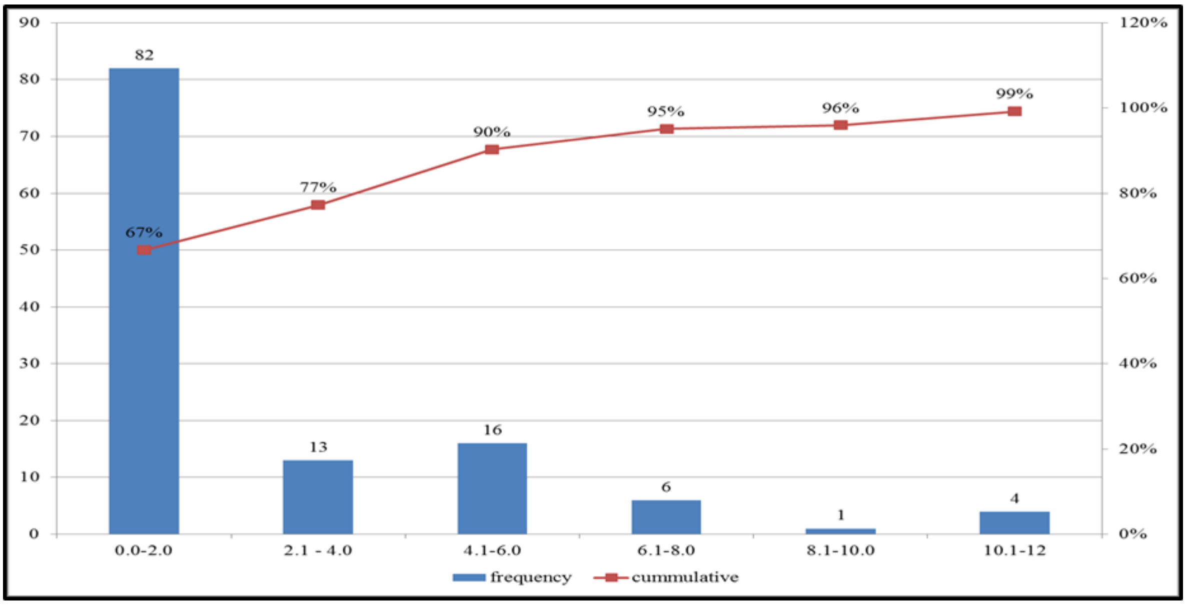

Figure 3-4: Relationship between sinkhole occurrence and thickness of the hards in the overburden overlying the coal seam.

- Sinkholes are unlikely to form in areas with parting thickness between the mined and unmined seams being greater than 1 m as indicated in Figure 3-5 and Figure 3-6 (81 % of sinkholes occurred in undermined areas with parting between the two seams less than 1m). Most sinkholes that occur in areas greater than 1 m parting thickness primarily occur after blasting under the weight of the dragline or during drilling under the weight of the drill rig especially in areas affected by spontaneous combustion as opposed to the classical progressive sinkhole formation.

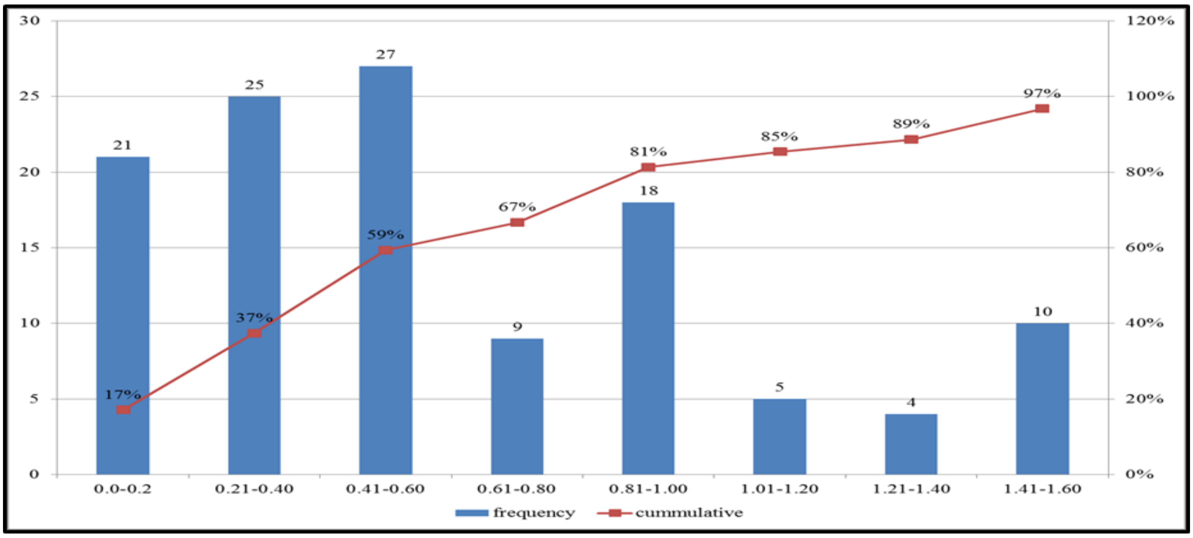

Figure 3-5: Relationship between sinkhole occurrence and thickness of the parting lying between the mined No.1 and unmined No.2 seam horizons.

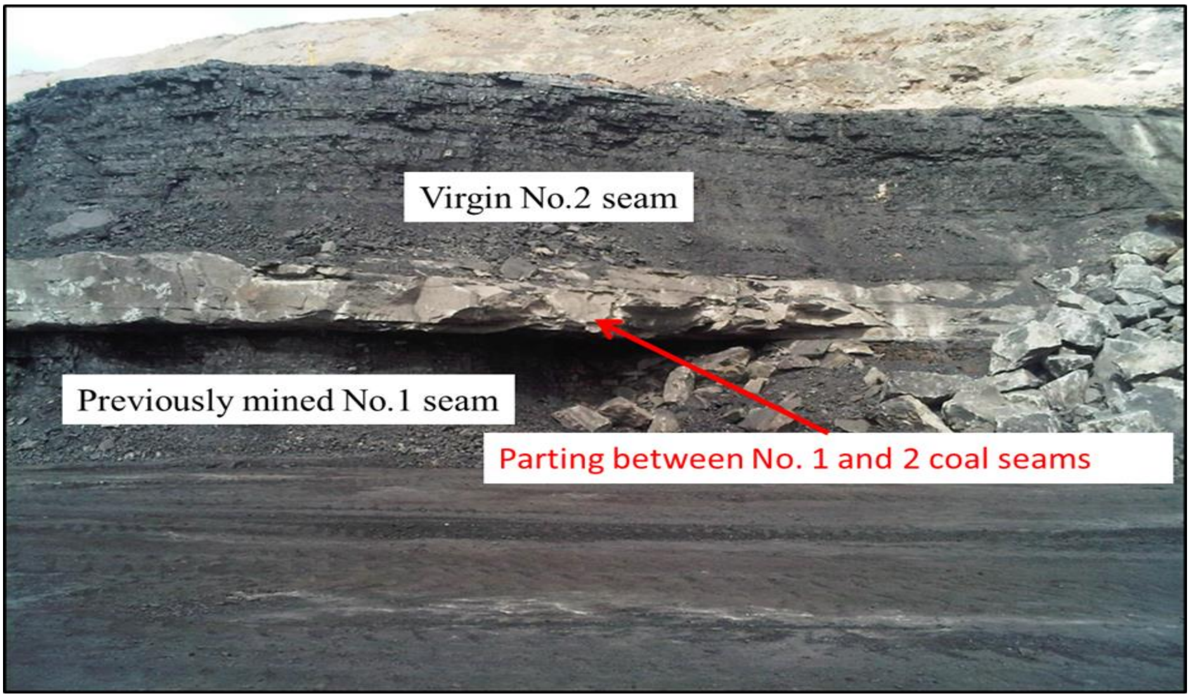

Figure 3-6: Picture indicating the relationship between sinkholes occurrence and thickness of parting between mined and unmined seam horizons.

- There was no correlation between the sinkhole occurrence and thickness of the unmined seam overlying the previously mine one as indicated inFigure 3-7, although a thin unmined seam could be indicative of the weathered unmined seam, thus implying compromised hards beam in the overburden.

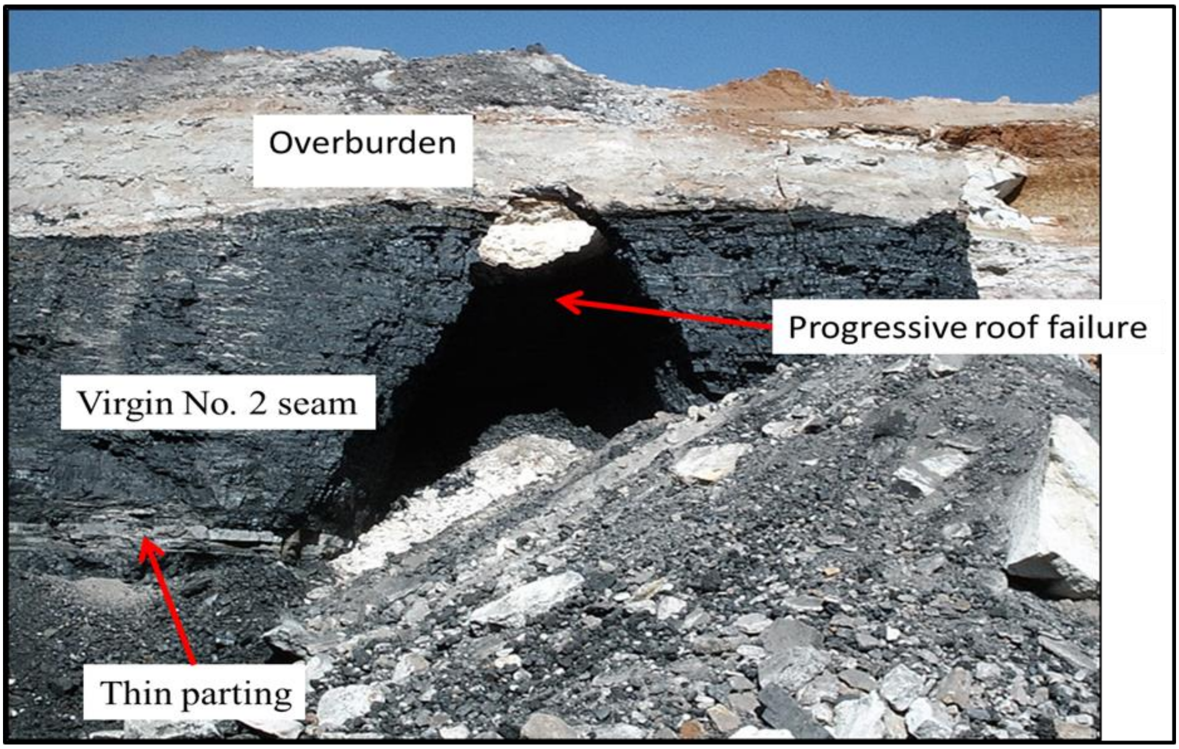

Figure 3-7: Picture indicating the sinkhole traversing through a thick unmined seam overlying a thin parting and mined No.1 seam.

- 98 % of sinkholes occurred in areas with overburden material comprised of soft overburden material less than 18 m as indicated inFigure 3-8. This correlates well with the world figure of 15 m which Hunt (1980) defined as the most sinkhole occurring predominant depth. This indicates that there is a higher propensity of sinkholes to occur in areas with overburden cover comprised of weathered material.

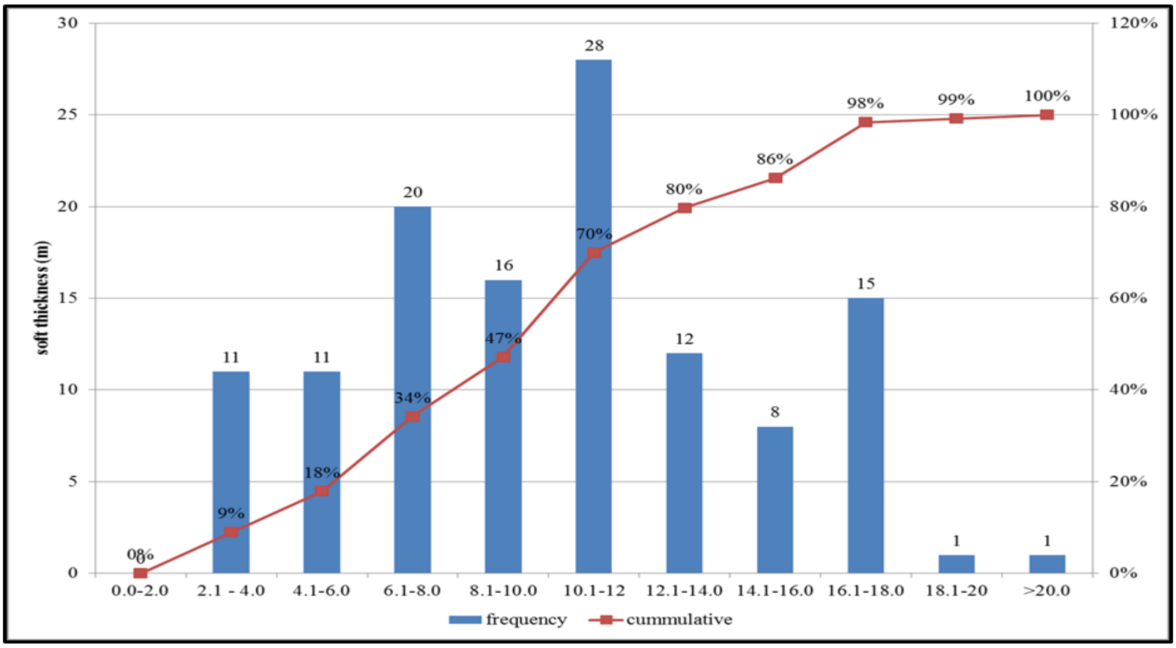

Figure 3-8: Shows the relationship between the softs overburden thickness and sinkhole occurrences.

- Most sinkholes were found in areas within proximity of the seam outcrops as depicted in Figure 3-9 thus indicating a higher propensity of sinkholes to form in near subsurface areas.

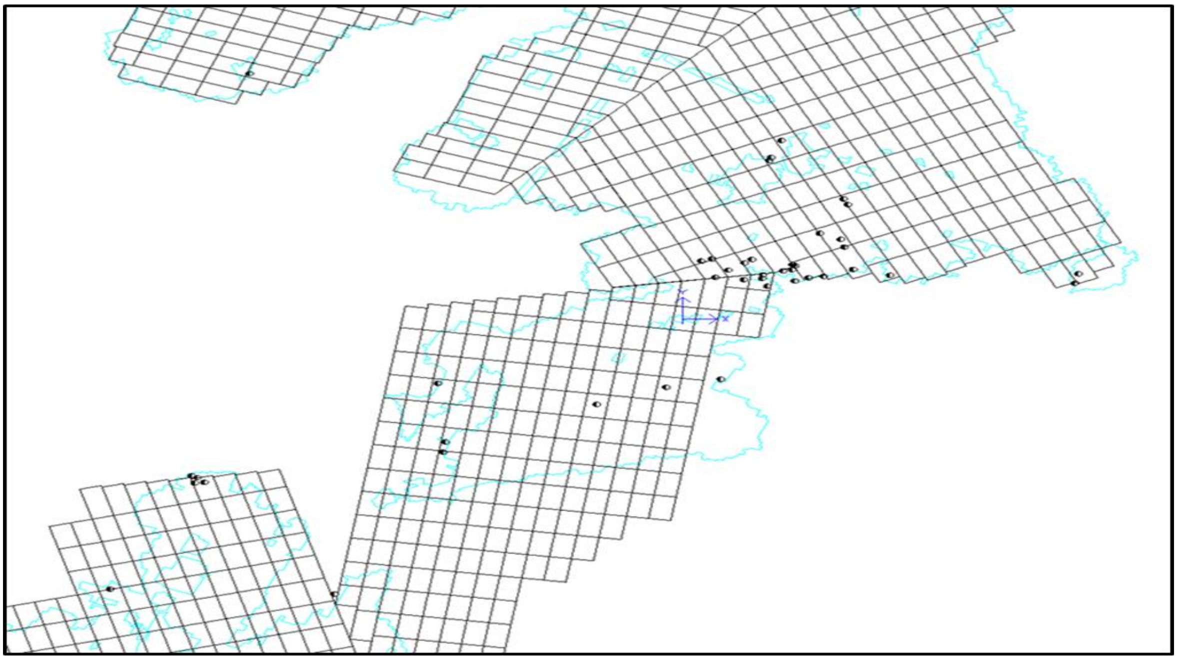

Figure 3-9: shows the predominant occurrence of sinkholes within the outcrop zones of the orebody as indicated by black dots.

Field inspections and composition analysis indicated the following

- Sinkholes were also found to occur in areas amenable to water accumulation (water collection points exposed to continual recharge and discharge, thus leading to chemical weathering as well as the washing away of the toe of the failed material).
- Sinkholes are likely to form in areas comprised of weak formation such as shales which are quick to degrade under water as opposed to areas overlain by sandstone and grit.

3.2.3 “Adopted Sinkhole Hazard identification Process”

The detailed studies of the field sinkhole database led to the adoption of the two tier approach to sinkhole hazard identification:

3.2.3.1 Tier 1 risk assessment

This process is a desktop study that predicts the potential for sinkholes to occur in a certain area based on the geological model for mining blocks measuring 100m by 60m, thus facilitating the division of the areas into high and low hazard zones as indicated by the flow diagram in Figure 3-10.

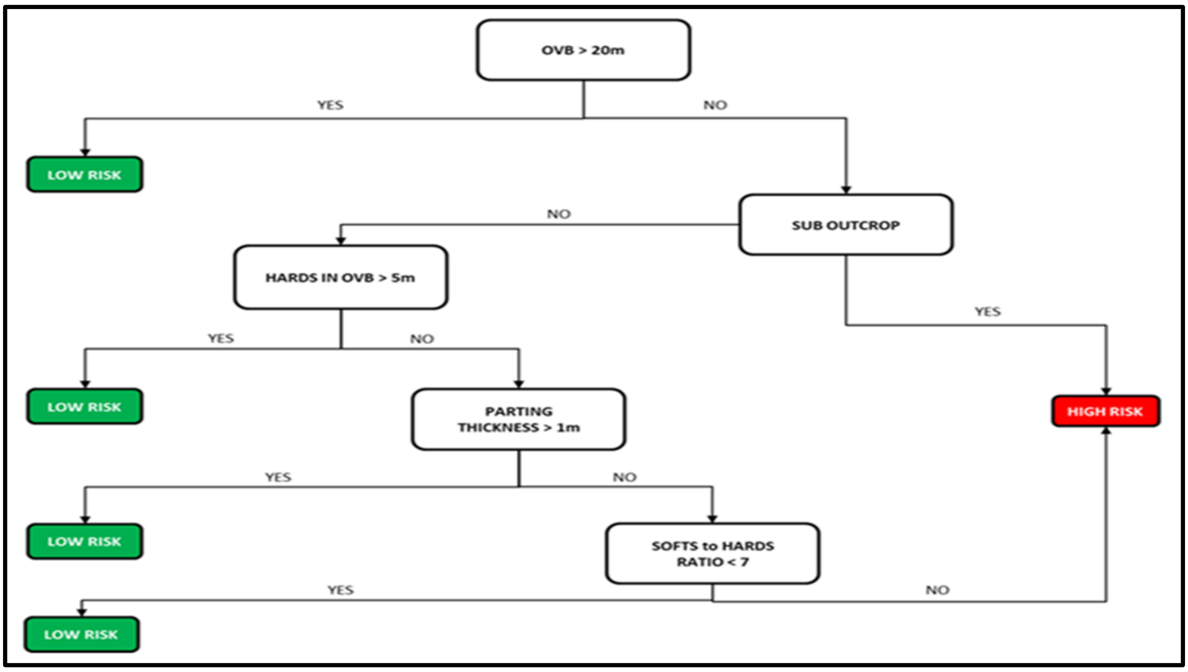

Figure 3-10: Flow diagram indicating the desktop Tier 1 process.

Tier 1 risk assessment process differentiates between high and low risk areas culminating in the production of a generic sinkhole plan as indicated in Figure 3-11.

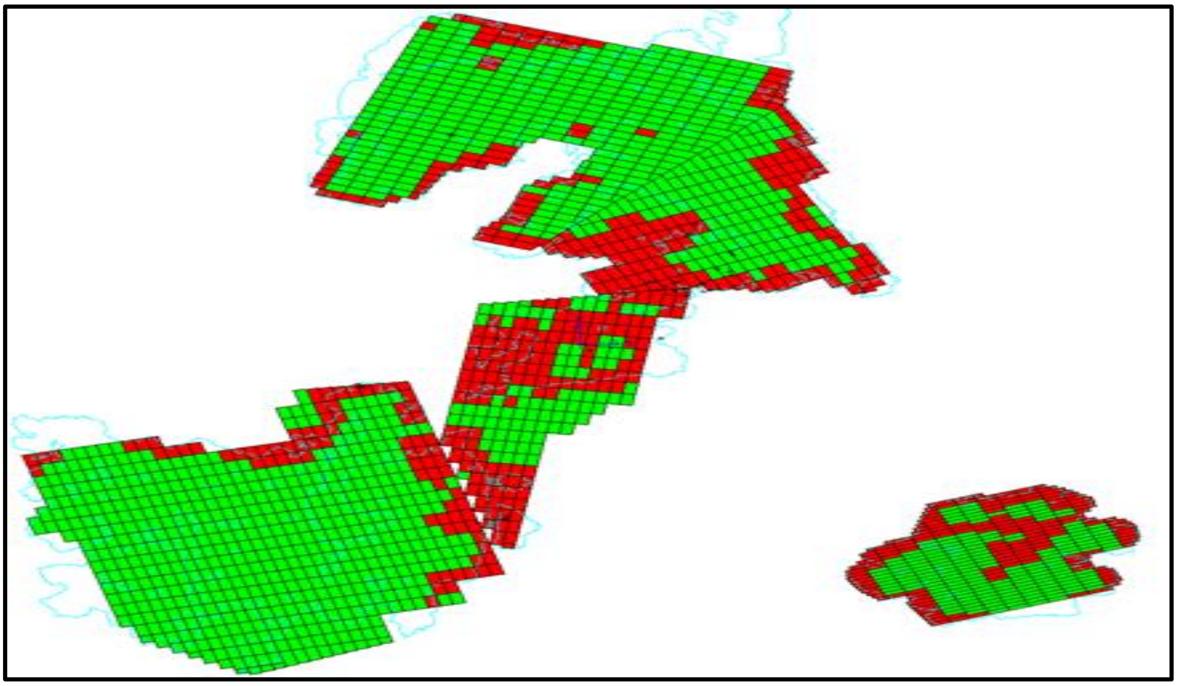

Figure 3-11: Generic sinkhole hazard plan based on Tier 1 process.

Tier 1 process also takes into account the following:

- Thickness of parting overlaying the old workings
- Thickness of hard material above the old underground workings
- The total overburden thickness
- The caving height (formation of a "chimney") as a function of the height of the old workings, bord width, angle of repose of the material and the swell factor.

3.2.3.2 Tier 2 risk assessment

Tier 2 risk assessment is conducted to confirm the results of the tier 1 (desktop study). This risk assessment process is undertaken by a multidisciplinary team comprised of mine planning, rock engineering, survey and mine production. Prior to the commencement of mining in a block measuring 100m by 60m and is called a strip, a full mining strip assessment will be carried out. This strip assessment will include a hazard identification, risk assessment and operational considerations.

The hazard identification and risk assessment will focus on the development of sinkholes and other geotechnical and mining hazards (highwall stability, spontaneous combustion, lowwall stability, activity interaction as well as mobile machinery). The following process takes place:

- All red and green blocks are subjected to this assessment
- Red remains red and can never turn green
- Green areas can be turned into red.

Tier 2 risk assessment process cognisance of the physical evidence from:

- Cloth plans
- Borehole logs
- Aerial photographs
- Field inspection

The above approach led to the Hill (1996) caving height approach being discounted to assess the propensity of sinkhole formation. The tier 1 approach is a desktop study that interrogates the probability of sinkhole formation based on the geology model subjected and now a function of the following revised criteria:

Area is considered low risk on per block by block basis if:

- Parting between Mined No 1 seam and unmined No 2 seam **(**P1) >1 m
- Hards in OVB > 5 m
- OVB > 20 m
- Old underground workings are not present
- Anglo American Coal Hazard Index (AMcoal HI) is less than 7.

In sub outcrop areas only 1 condition should be satisfied:

- OVB > 20m

This led to the classification of mining blocks into two risk categories as opposed to the original three as follows as indicated in Figure 3-12.

- Low risk areas are colour coded “Green”
- High risk areas are colour coded “Red”

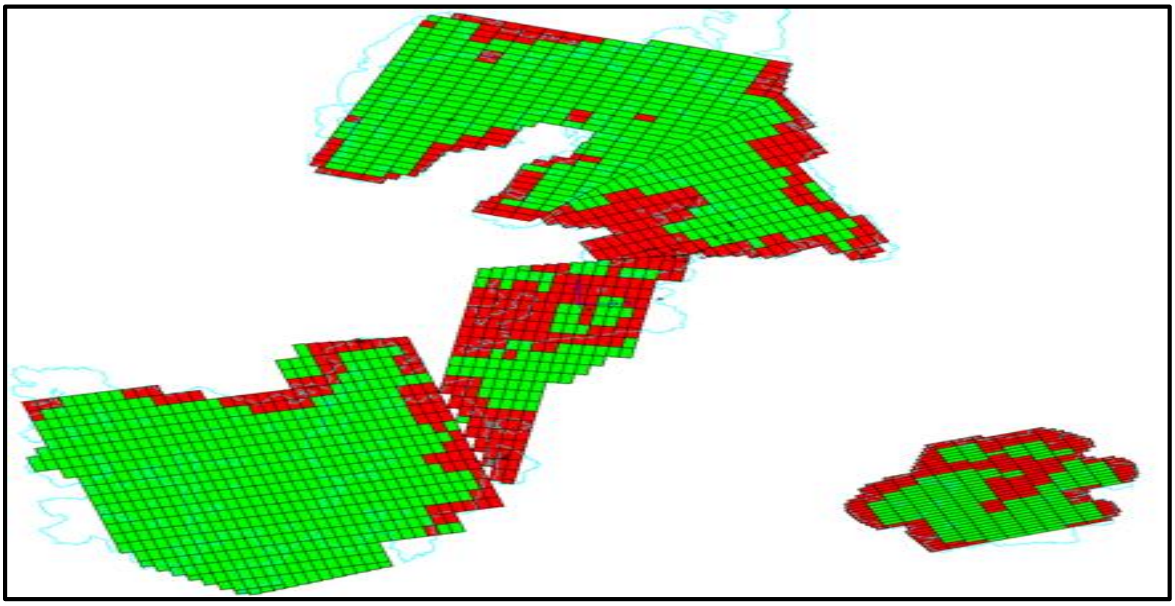

Figure 3-12: Plan the desktop “Sinkhole Prediction Model” for mining blocks measuring 100m by 60m in the mining window under the refined Model.

3.2.4 Shortcomings of the Adopted sinkhole hazard identification process (“SHIP”)

Following the adoption of the two pronged approach to sinkhole hazard identification the residual risk of sinkholes culminated in two sinkhole incidences as indicated in Figure 3-13 and Figure 3-14.

Figure 3-13: The dragline stuck in the residual sinkhole as indicated in the above picture.

Figure 3-14: Sinkhole occurrence in block lying in juxtaposition to blasted ground (linked to blast vibrations and weak lithology in the overburden).

The residual sinkholes were primarily occurring in the following areas:

- Ground shaking due to blast vibrations led to increased occurrence of cavity formation risk on rehabilitated ground (roughened up) as well as levelled areas inclusive of drill benches and dragline walkways.
- Weak lithology in the overburden (roughened up areas) – areas comprised of shales which are amenable to undergo further degradation when exposed to vibrations (due to blasting and equipment as well as machinery weight) and water (chemical change of shales to clay, as well as repeated contraction and expansion), thus leading to elevated cavity formation.

The gap created by the above two occurrences led to the need to further refine the sinkhole management tool to facilitate minimal production stoppages as well as eliminate residual sinkhole incidences in the operation.

This led to the introduction of a detailed analysis of borehole logs to assess the presence of weak strata in the overburden (which contribute at least 99 % of sinkholes as indicated in Figure 3-15) that has greater influence to sinkhole occurrence.

- ➢ Lithological analysis as indicated in Figure 3-15 and Figure 3-16 was undertaken and this led to the development of an additional criteria for managing areas comprised of weak overburden material, which culminated in the if (and condition) being adopted. An area will be classified as "Deep Red Area" if the following conditions are met:
    - Total OVB < 15m and
    - Thickness of hards in OVB < 1m

This led to a revised hazard plan for sinkhole management. An example to one of the revised plans is provided in Figure 3-17. The abbreviations in Figure 3-15 are defined as follows:

TOPO- refers to a topographical surface.

BHSO refers to base horizon of soft overburden material

BHWE refers to base horizon of weathered material

TOC refers to top of coal

BOC refers to bottom of coal

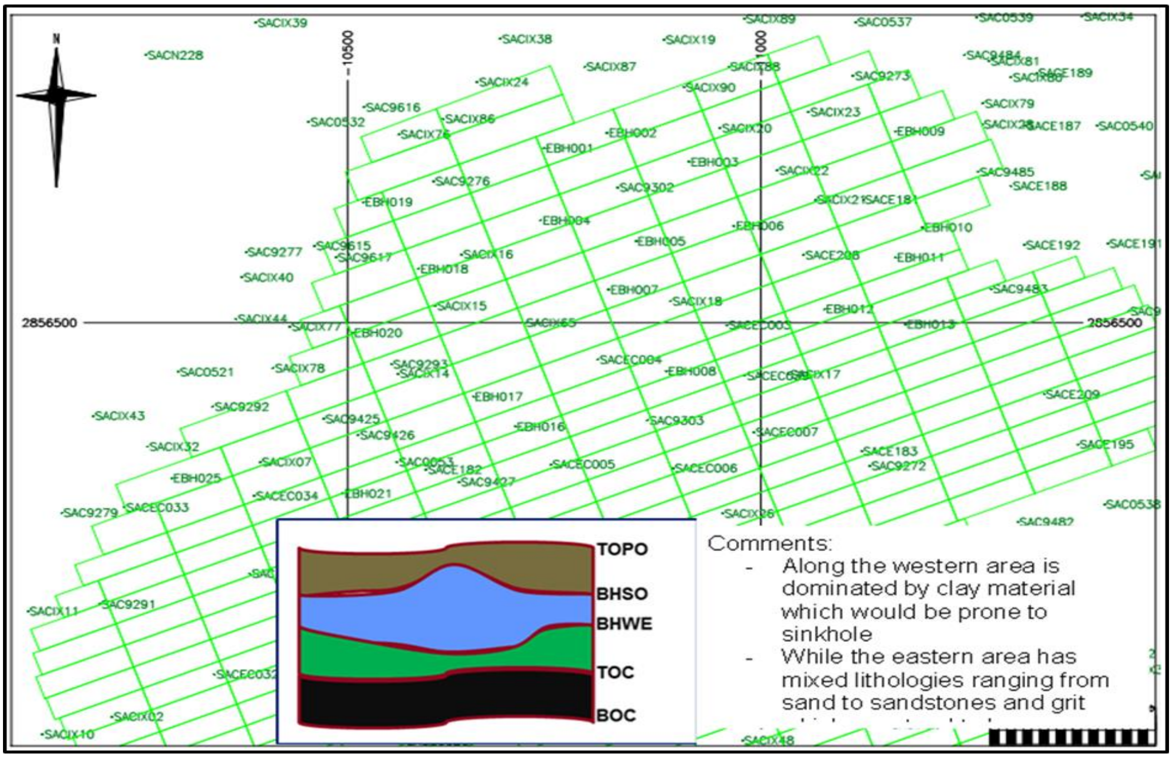

Figure 3-15: Plan view indicating the areas subjected to lithological analysis based on borehole logs.

Weak overburden material refers to material that can be mechanically excavated by a shovel or dragline without having been blasted as indicated in Figure 3-16.

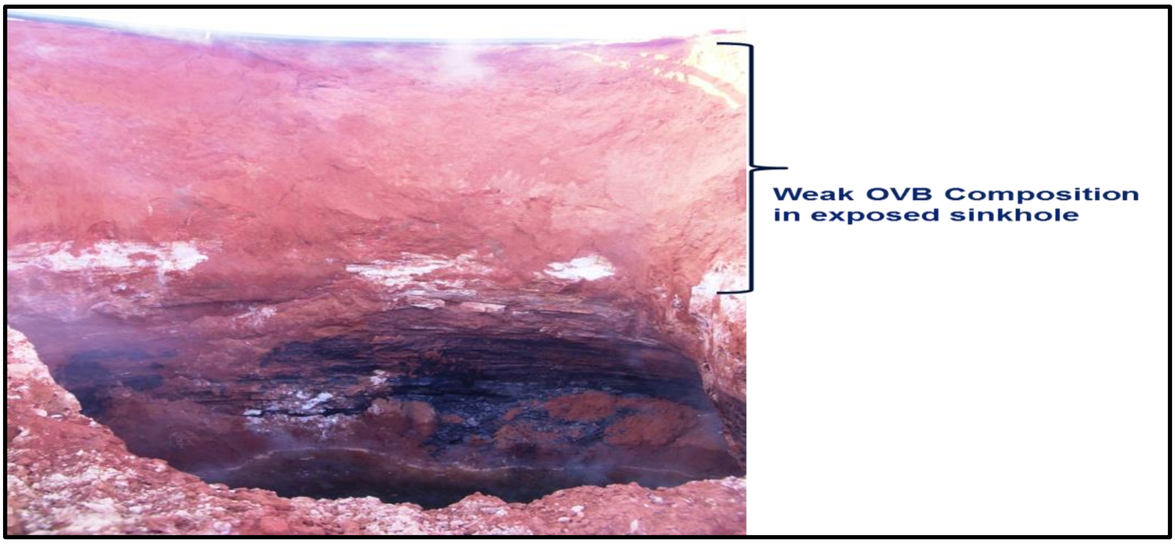

Figure 3-16: Down sinkhole section indicating the weak overburden material above the coal seam.

This led to the development of “Deep Red Areas “(Red #) classification as indicated in Figure 3-17.

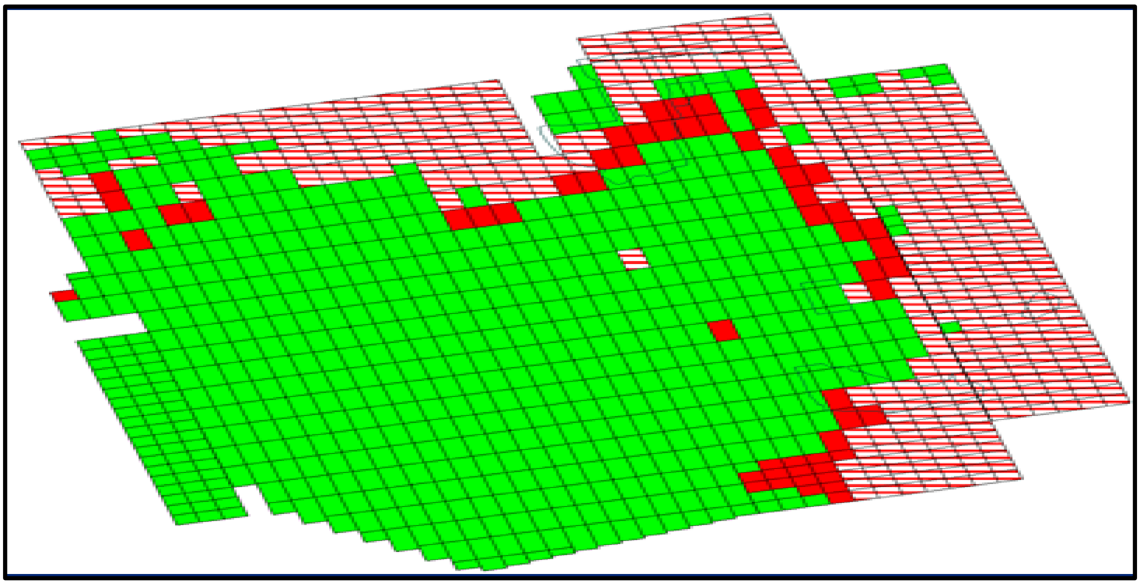

Figure 3-17: Plan indicating refined Adopted “Sinkhole Prediction Model” incorporating Red # (Deep Red Areas) in areas associated with weak lithology.

3.2.4.1 Refined “Adopted Sinkhole hazard Identification Process”

The refined model was adopted as the credible sinkhole prone area identification and is indicated in Figure 3-17. This is a desktop study which is an outcome of the Tier 1 and 2 approaches to risk identification. This is further augmented by the Tier 2B process which is a detailed reconciliation process that ensures both the chimney (geometry related) and any residual sinkholes (blasting induced) are fully eliminated thus leading to safe mining execution within a given mining block. This system is quite robust and has managed to offer a methodology which for now can be described as “Full Proof” and is capable of identifying the sinkhole risk prone areas.

3.3 **Summary**

This chapter discussed the problem of how to predict the areas with sinkhole risk. The problem was resolved by using an automated sinkhole prediction method (tier 1) in conjunction with physical evidence of the conditions around the area to be mined (tier 2).

The chapter discusses the various enhancements to the “Sinkhole Prediction Model with the aim of producing a robust system of ensuring coal extraction optimisation without exposing equipment and personnel to unsafe conditions. The next chapter discusses the primary sinkhole rehabilitation process and the refinements to enhance coal extraction safely.

4 SINKHOLE MANAGEMENT PROCESS

4.1 Access control

Once an area has been identified as having potential for sinkhole formation (Tier 1 process) and confirmed by the Tier 2 process, the area should be marked by "Red" and "Green" boards placed in conspicuous places for high and low risk areas respectively, for the purpose of access control as indicated in Figure 4-1 and Figure 4-2. This is done to safeguard both personnel and equipment. Areas with sinkhole potential are not accessed with people on foot during day and night shift. Only equipment with provision of adequate plant lighting are used in areas with sinkhole risk at night.

Figure 4-1: Access controls for High risk areas (Red # and Red).

Figure 4-2: Access controls associated with Green areas (Low risk).

4.2 Rationale of the roughening up process

Currently this work is contracted to a company called "BBT" who are specialists in sinkhole stabilisation. The contractor is required to firstly strip and reclaim topsoil to the required depth within the equipment reach from a stable area as indicated in Figure 4-3. The topsoil is to be 'live' (live placement refers to the digging of the topsoil and immediately takes it to the place to be rehabilitated without stockpiling it) placed dependant on placing area availability or stockpile in areas identified by the mine. Reclaiming of topsoil is essential to prevent loss of topsoil in the roughening up process required to stabilise the hazardous areas. On average 50 000m^3 of topsoil is planned to be stripped per month depending on mining areas and conditions. The stabilisation of hazardous red areas requires excavation from a stabilised area down to a depth of 5-6m within equipment reach.

Figure 4-3: Top soil reclamation in areas to be roughened up (High risk).

Roughening up is a method that is used to make the area prone to sinkhole formation safe prior to conducting activities. The digging depth is limited to a maximum depth of 6m.

The roughening up process which is a method used to stabilise areas amenable to sinkhole formation during either top soil removal or overburden drilling as detailed in the following section.

Prior to roughening up the following process is followed:

- A roughening up plan is generated for each area (block measuring 100m by 60m). This plan is accompanied by a cross section indicating the anticipated digging depth (4-6m) or until intersection of a competent beam whichever comes first from a stationary position.
- The underground workings in the planned roughening up area are pre-loaded onto a global positioning System (GPS) to guide the surveyor to travel and walk in a safe area free of potential void collapses.
- The surveyor demarcates the starting position for the roughening up at least 30m away from the edge of the underground workings for the block to be stabilised as indicated in Figure 4-4. The roughening up machine will commence the

stabilisation of the sinkhole prone block from a known stable ground as indicated in Figure 4-4. The underground edges are known from the survey plan of the previously mined workings.

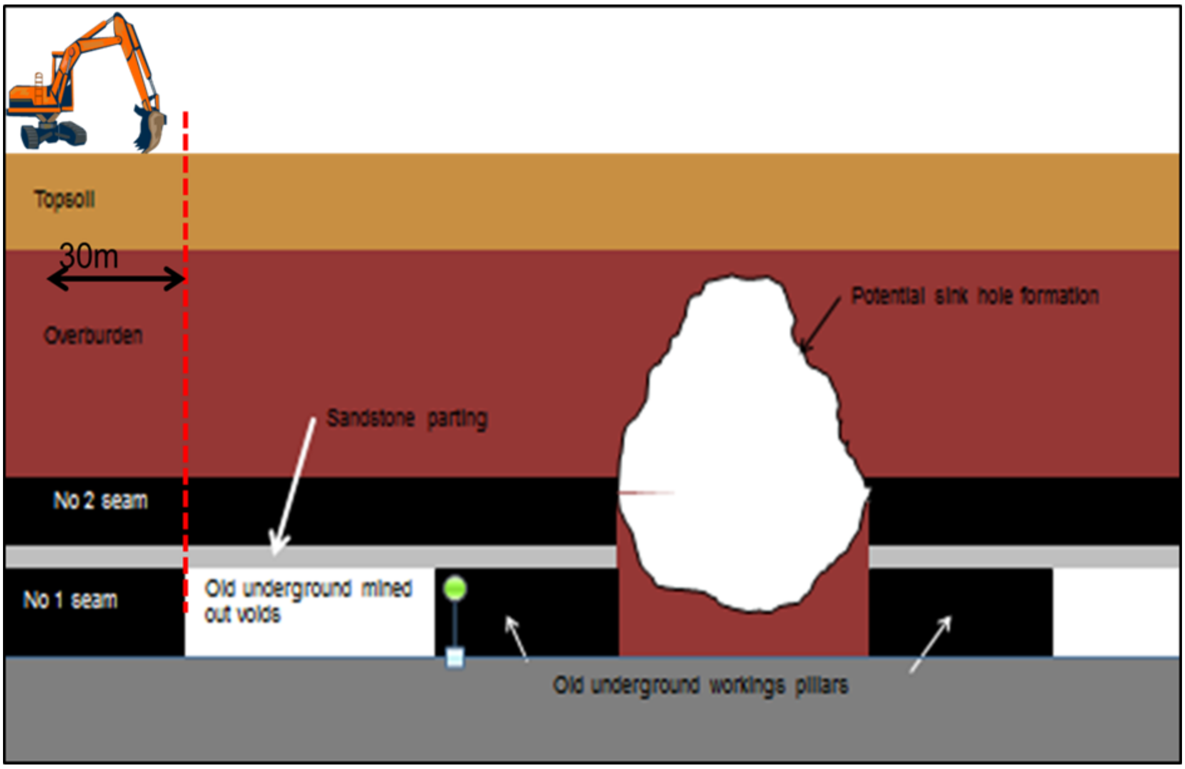

Figure 4-4: The roughening up starting position 30m away from the edge of the known underground workings (High risk areas).

- The stabilising process always commences from a known stable ground 30m away from the edge of underground workings as indicated in Figure 4-4, thus ensuring guaranteed safety of personnel and equipment.
- Excavator positions the bucket as indicated in Figure 4-4 on the marked starting point and commences digging towards the high risk zone. The digging process takes place for at least the boom length advance whilst excavator is in one stationary position as indicated in Figure 4-5.

Figure 4-5: The Sinkhole exposure process

- Excavator also strips the topsoil that is within the reach of boom and places it onto the tipper positioned behind the excavator on stable ground, thus facilitating recovery of topsoil in high risk areas.
- After the topsoil removal the subsoil / weathered material inclusive of any other mechanically free removable material are placed on the sides of the area to be stabilised. If required, excess material will be loaded away with another excavator and trucked away.
- The machine then digs to a maximum depth of 4-6m based on machine reach or until a hards material beam has been intersected. The machine then presses the bucket on the exposed beam to ascertain the competence of the intersected maximum digging depth or beam. This process of imparting force on the exposed beam is called “probing”.

- After probing and ascertain the horizon competence the side stacked material is filled back to cover the created void as indicated in Figure 4-6.

Figure 4-6: The backfilling of the created void in high risk areas by Dozers.

- The excavated area is then backfilled with a dozer as indicated in Figure 4-6 and compacted by the roller as indicated in Figure 4-7 before moving forward to the next area for stabilisation, thereby ensuring people and equipment are always on stable ground.

Figure 4-7: The compaction of the backfilled void by the roller in high risk areas.

- Once the void in front of the Excavator is filled and compacted, the Excavator must slowly advance forward half of the boom length as indicated in Figure 4-8.

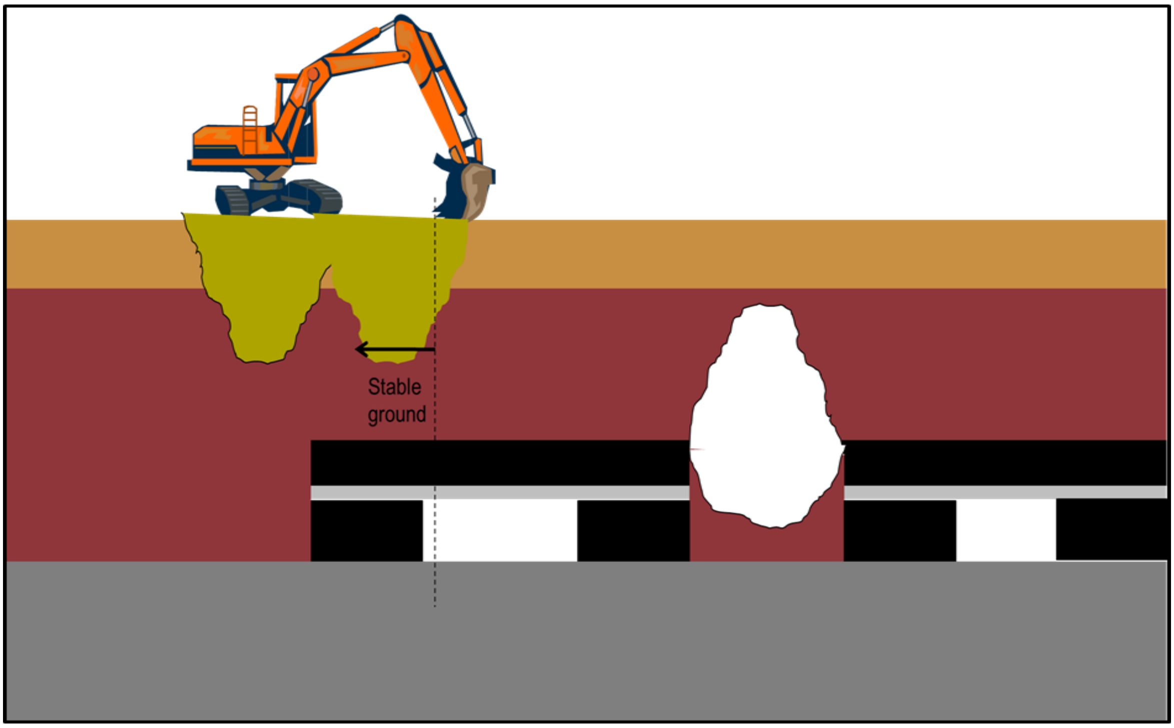

Figure 4-8: Excavator forward movement after stabilisation of dug void (High risk areas).

- If at any point the topsoil stripping or stabilising of potential sinkhole area becomes unsafe due to cavity manifestation the work will be stopped and the area barricade off. The area will be reported to management upon which an inspection will be conducted prior to commencement of the roughening up process.
- The above process is repeated until the entire block has been stabilised.

Any sinkholes identified during the roughening up process are reported and are surveyed and the database will be updated accordingly. The sinkhole will be analysed to ascertain the correlation between the sinkhole characteristics against the criteria of overburden thickness, hards composition, softs to hards ratio and parting thickness. This is done to check the integrity of the set criterion of sinkhole prediction.

4.2.1 Roughening up Quality

The roughening up quality is aimed at ascertaining if work has done by the contactors to the required specifications. The detailed check of the contractor quality work execution is as follows:

- Roughening up quality inspections are conducted twice per week by the strata control officer and the Assistant pit superintendent.
- The digging up depth is compared to the planned digging depth as provided on the cross section. This serves as a reconciliation process thus ensuring the guaranteed credibility and quality of the roughening up process.
- Where planned digging depth do not match the sections the information is fed back to adjust the geology model and new cross sections generated to inform the future roughening up in the forward blocks in the direction of mining.

4.3 Limitations of sinkhole management

Following the implementation of the sinkhole management the following challenges were realised.

- Occurrence of sinkholes in roughened up areas ahead of the blasted benches.
- Occurrence of residual sinkholes in blasted areas.

- Roughening up of entire mining block measuring 100 m by 60 m is time consuming (targeted roughening up not feasible due non availability of equipment to locate exact location of the actual void).
- Roughening up of a 100 m by 60 m mining block is costly and is equivalent to the cost of rehabilitating one sinkhole and is approximately R3.5 million, which translates to R7/sales tonne.

In order to curtail the challenges alluded to above the following rigorous refinements as discussed in section 4.4 had to be undertaken.

4.4 Enhancements to sinkhole management

4.4.1 Minimisation of Sinkholes in treated areas (adjacent to blasted benches).

To address the pitfalls of the roughening up process the following robust controls were then initiated:

Stringent controls were implemented to ensure consistence in the quality of work undertaken by the contractor includes reporting and recording of any identified abnormalities picked up during roughening. This led to the further affirmation of a robust self-auditable system aimed at enhancing the quality and quantification of the roughening up process. Areas that would have gone beyond two months as indicated in Figure 4-9 before blasting had to be re-assessed and roughened up if necessary. This was to cater for any potential cavities that would have progressed due to blast vibrations from the adjacent blocks.

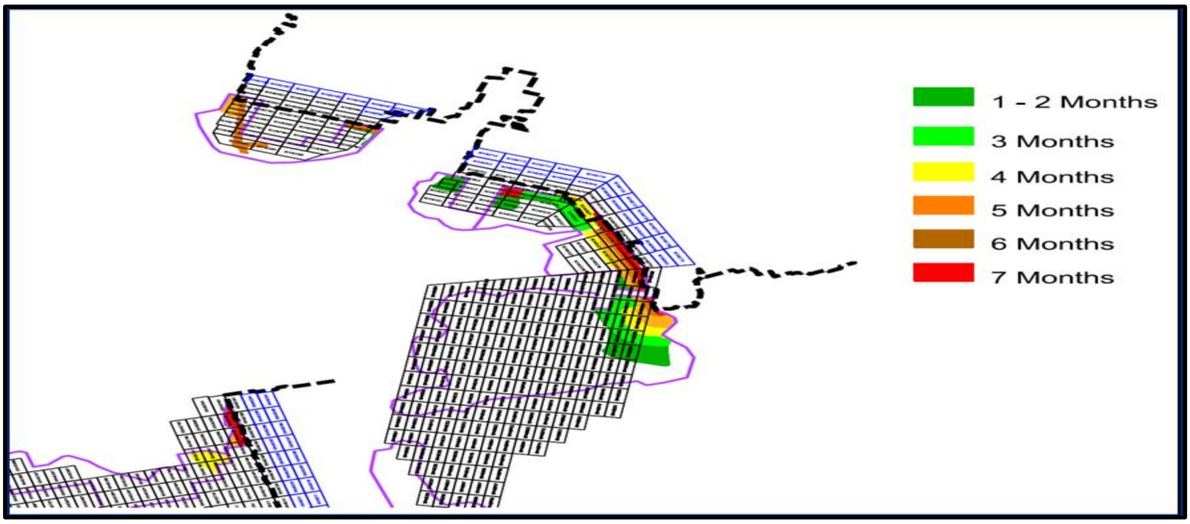

Figure 4-9: Trigger plan indicating the lag time lag between roughening up and blasting.

4.4.2 Blasted areas "Residual sinkhole elimination"

In order to ensure total elimination of sinkholes in blasted areas the following robust method was introduced to ensure complete collapse of the voids, thus eliminating the occurrence of residual sinkholes (occurrence of sinkholes in blasted areas):

Drill and blast reconciliation process as indicated in Figure 4-10 was introduced to ensure the success rate of the drill and blast process. This was aimed at ensuring drilling and blasting accuracy, thus ensuring total void collapse in all blasted benches. The success rate of this process is a function of the accurate position of the pillar in the given mining layout.

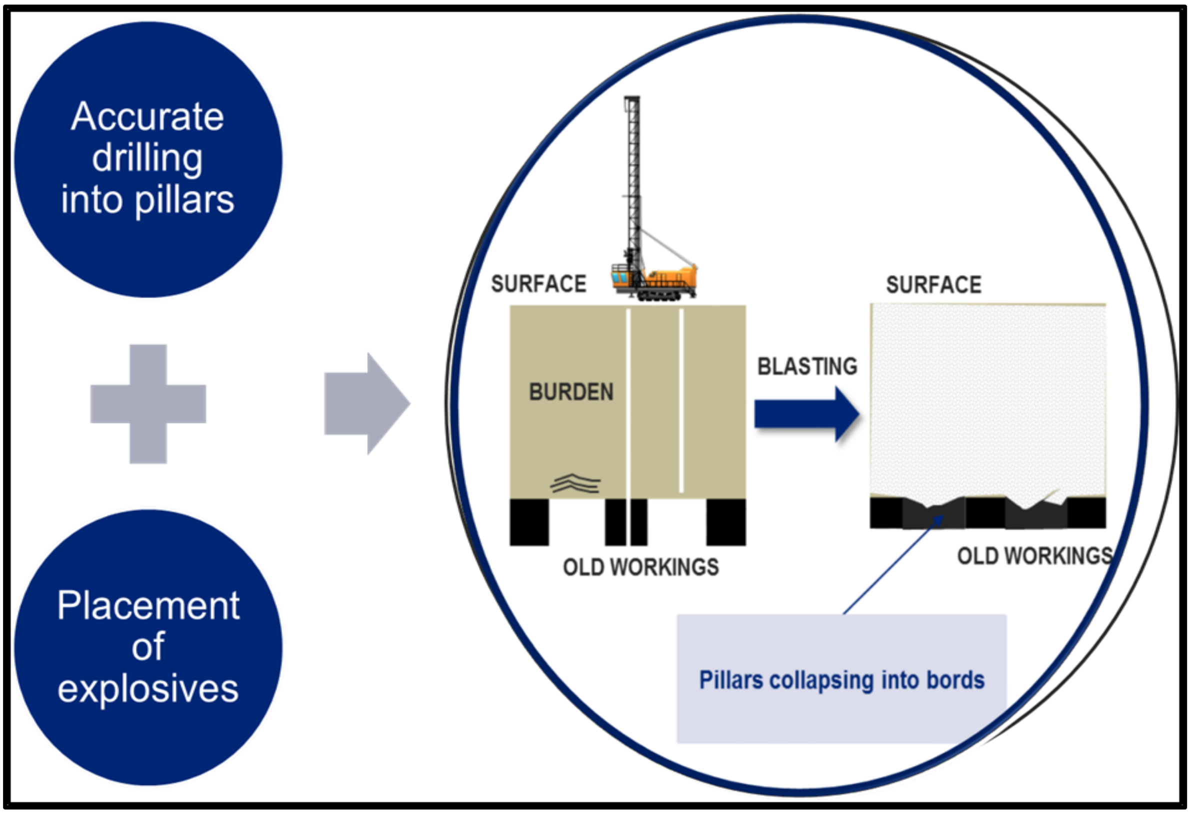

Figure 4-10: Schematic sketch indicating the reconciliation process between drilling and blasting to ensure total void filling.

4.4.3 Precise sinkhole identification

A rigorous risk assessment programme aimed at evaluating the extent and impact of sinkholes or subsurface cavities was undertaken, with a view to developing a comprehensive sinkhole identification and elimination method to the risk posed by these sinkholes.

An asset optimization project was commissioned in early 2012 to develop a technique for the autonomous detection of voids within the first 20m of ground surface. Several geophysical techniques were selected for field testing. Results were encouraging for the further development of the Ground Penetration Radar (GPR) and Multichannel Analysis of Surface Waves (MASW-ground static or moveable) techniques to assist in the correct and precise identification of sinkholes or voids.

4.4.3.1 Terra Vision Ground Penetration Radar (GPR)

A test site to facilitate the void detection capabilities of the GPR technique as a viable operational tool for the routine scanning of mining blocks to detect the presence of residual voids prior to mining was undertaken. Both conventional and unconventional GPR technologies were validated at a prepared site in the group. The Original Equipment Manufacturer (OEM) with a GPR capable of being realistically deployable, robust, and provides real time indication of void locations, including historical underground workings was selected.

Proceedings from the void detection trials held in 2012, identified the GPR as one of the geophysical techniques which showed capabilities of imaging voids within the first 20m of the subsurface and the method showed great results with penetration of up to 14m obtained at a test site in the group.

The GPR void detection went into another phase, where its capabilities and operational viability were investigated and tested on a representative ground which simulates underground voids known to exist at site X. This phase of the project involved erection of a representative site with water drums of different sizes buried at different depth to represent existing voids. The various drums of different sizes were buried at depths between 2m and 6m. Multichannel Analysis of Surface Waves (MASW) and TerraVision-Radar (TVR) a 4th generation ground penetrating radar system with the pulse transmitter power increased to 100 000 times the power of a conventional system were used to facilitate the detection of imaginary voids.

4.4.3.2 Multichannel Analysis of surface Waves (MASW)

The MASW was validated at site X. The acquisition of several lines of MASW data totalling 300-400m were completed in just over two days. The technique indicated that under full production mode data acquisition would be sufficiently rapid. Data quality was found to be good with average penetration rates of 12-30m. The method indicated that under full production mode data acquisition will be sufficiently rapid thus allowing for timeous decision making by management. This will ensure non production delays, thus enhancing productivity.

4.4.4 Results

The results indicated that the GPR was the preferred tool for deployment compared to the MASW due to the following reasons:

- GPR is cheap, readily accessible and deployable in an autonomous mode.
- Relatively little processing time compared to other geophysical survey techniques
- Data processing is rapid with potential for overnight processing with positional accuracy supported if system is fitted with a Differential Global Positioning to enhance data quality (more accurate location of the anomalous responses in real time).

4.4.4.1 Weaknesses of void detection system (GPR)

During the test work at site X and Y the GPR system as indicated in Figure 4-11 was set to assist in identifying the buried "Jojo "tanks (representing underground voids or sinkholes at depth) at variable depth. The GPR was deployed in a selected block as indicated in Figure 4-12.

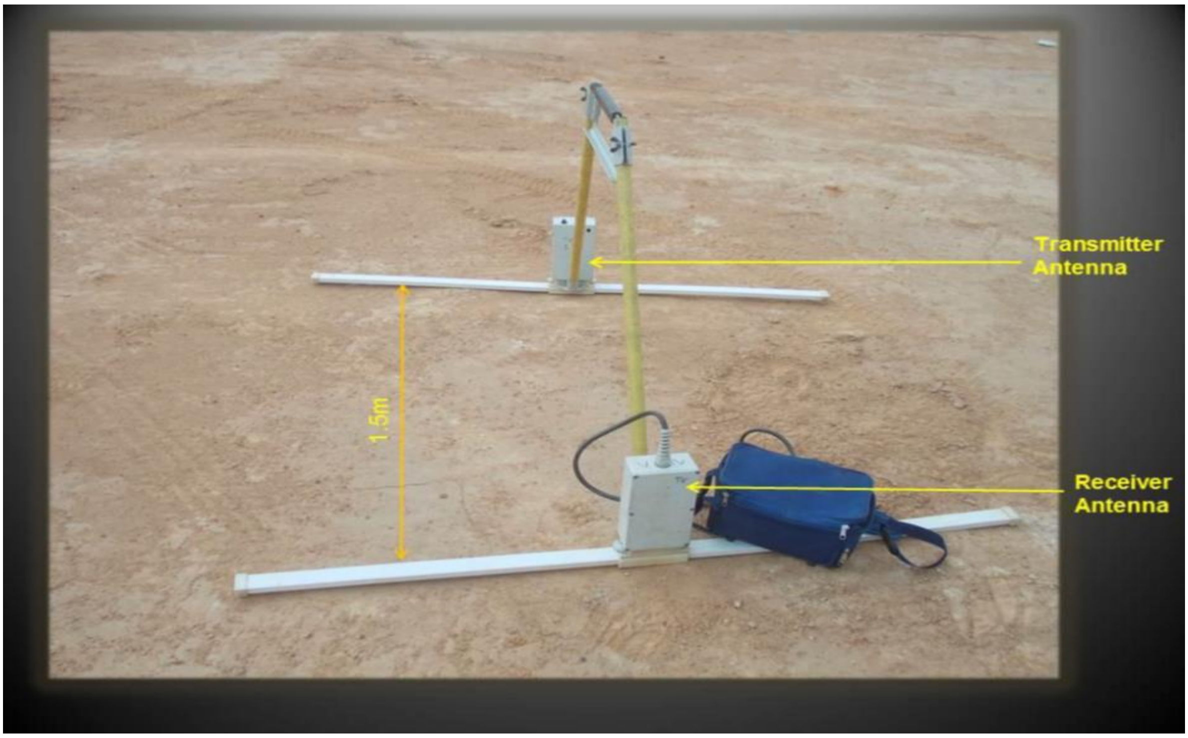

Figure 4-11: GPR system deployed in the field to detect buried tanks at variable depth.

During the test work the following flaws were identified:

- The anomalous point picked by the GPR did not correlate with the georeferenced buried "Jojo "tanks position
- In areas with geological anomalies such as faults, the GPR picked these as buried tanks, thus indicating the system's inability to distinguish between geological anomalies and voids due to underground workings.
- Penetration rates of a low as 1-3 m metres were recorded for areas overlain by conductive layer such as shales and wet rock formations. This indicated the limited application of the system in areas overlain by wet and conductive rock formations.
- Not practical to deploy routinely in closely spaced lines (less than 1.5m) to facilitate detection of the smallest possible void.

Figure 4-12: Selected test block (Yellow) where tanks were buried (Pink text).

4.4.5 Cost reduction

The need to reduce the cost of rehabilitating sinkholes still remains a challenge. This could not be mitigated since the autonomous void detection systems pursued could not assist in precisely and accurately pinpointing the actual sinkhole position to inform point rehabilitation thus saving cost of digging and backfilling the entire 100m by 60m block.

4.5 **Summary**

This chapter discussed the sinkhole management process in this research report by giving some of the pertinent issues regarding the rationale of the sinkhole stabilisation process including the pitfalls and refinements that were undertaken to ensure robustness in the system which is meant to mitigate the loss of life and equipment. The inadequacy of the trialled void detection system was also discussed. The void detection was aimed at assisting in the exact location of the void or sinkhole with a view to guide targeted roughening. Targeted roughening up would mean only digging and stabilising the void in the exact location as opposed to digging an entire block measuring 100m by 60m,thus leading to reduced roughening up costs. The next chapter concludes the research and recommendations to ensure sustainability.

5 CONCLUSION

5.1 Chapter overview

There is need to develop a sinkhole risk mitigation process that is robust and sustainable. The current status is that the implemented process has managed to eliminate the incidence of sinkholes and equipment damage but still incurs a huge cost to the company. This observation was corroborated by the failure to implement an autonomous void detection system that can enable the treatment of a void at a point within a spatial block measuring 100m by 60m. This will lead to reduced roughening up costs as the process will be targeted at a specific point that is amenable to collapsing impacting on activities above the void horizon. The aim of this research was to develop a robust method of identifying the potential zones in which sinkholes are likely to form as well as develop a method for treating these voids thus mitigating the loss of life and equipment. This research has managed to largely achieve this aspect in addressing this major milestone. The research report sort to develop a system to facilitate safe coaling in previously underground mined workings with a view to manage the sinkholes within Anglo Coal operations.

5.2 Contribution

The methodology for sinkhole prediction is primarily underpinned by the following three parameters:

- The thickness of depth of overburden cover, composition of hards in the overburden and thickness of parting (separating the mined and unmined seam horizons)

The methodology was empirically developed and later affirmed by back analysis of the actual sinkhole incidences (over 100 sinkholes to date).

These parameters were identified to correlate well with development of sinkholes and now form the main criteria in the development of the sinkhole hazard plan. There is a need to augment the locked in parameters with the following process:

- An analysis of the lithology will assist in zonal division of areas based on rock formations that have an elevated sinkhole formation potential.

- Implementation of a robust roughening up quality audit is crucial to the success of the sinkhole treatment.

- Drilling and blasting accuracy aimed at completely collapsing the underground workings would lead to total elimination of residual collapses on blasted benches (which is a function of the correct identification of the positions of the underground workings).

- Timing between roughening up and blasting is of prime importance as the sinkholes are likely to reoccur in previously rough up areas, primarily due to ground deterioration arising from blast vibrations of adjacent blocks.

- There seems also to be merit in pursuing automated mining though this exposes equipment (equipment damage due to falling in voids or sinkholes) and personnel (falling into voids during equipment retrieval process).

The way forward, in the absence of a well-known and scientifically proven precise sinkhole prediction model is to make use of the following

- Critique of the prediction process
- Implement stringent controls on accurate drilling and blasting
- Implore roughening up to yield desired results.
- Understanding the influence of the time lag between roughening up and blasting to sinkholes occurrence.

Sinkhole prediction process should be developed based on site specific data in order to produce a robust tool for sinkhole management. The theoretical basis should form the initial backbone of the prediction model and this should be subsequently refined to align the prediction to actual sinkhole occurrence. The analysis of sinkholes after exposure and establishment of a database cannot be over emphasised. This in itself reflects a new way of seeking answers to sinkhole challenge thus leading to the development of a sustainable system to manage sinkholes. In the past, mines used to depend on the caving height formula as first discussed by Hill (1996) which was based on geometrical considerations. Geometrical considerations are variable and site specific and are thus not robust enough to cater for variability in mining environment dynamics. This research report recognised the diverse changes in conditions and ground response in areas lying in juxtaposition thus indicating the need to zone areas to assist in better management of the hazards. Having a database that is capable of capturing information from the entire population coupled with the potential to be updated over time presents a powerful tool to deal with sinkhole management. This research has also managed to set the scene by indicating the limited application of the GPR system as a void detection tool in conductive and wet rock formations including geological anomalies.

5.3 **Limitations and constraints of the project report**

Although this research report has achieved its aim, there are some limitations and constraints which need to be considered. These are:

- Inability to precisely identify the actual void location to facilitate location specific treatment, thus reducing rehabilitation cost (TerraVision could not yield meaningful results).
- Reliability of data (ability to distinguish between naturally forming voids and blast related ones).
- Understanding of sinkhole formation dynamics and ground response.

5.3.1 Lack of precise void identification

The roughening up process is a costly exercise as it involves searching for voids in the entire mining block measuring 100 m by 60 m. This is associated with high costs and there is need to invest in precise void detection methods to guide roughening up of problematic zones within the mining block. There seems to be merit in initiating serious research work in order to fully understand the sinkhole formation dynamics. This will assist in giving insights as to the route to take in order to accurately and precisely identify the next sinkhole position with a view to facilitate targeted rehabilitation. Use of improved hybrid modelling techniques such as “ELFEN” might be worthwhile.

5.3.2 Reliability of data

There is need to distinguishing between naturally forming and blast induced voids. This would assist in reducing errors creeping into site specific sinkhole prediction models. There is need to enforce detailed investigations to ascertain the root cause of the void prior to its incorporation into the database informing the sinkhole prediction model by the rock engineering department on each site or operation. Currently this is being hampered by mistrust and lack of trustworthiness, thus leading to inclusion of redundant data that will lead to skewed analysis. This will lead to errors creeping into the back analysis thus leading to poor correlations and onerous predictions. This can be eliminated through documenting a set of characteristics that distinguish between a naturally forming and blast induced cavities. This should also be followed by digging up process to expose the cavity for assessment thus leading to accurate classification. To the extent possible, the researcher verified the information provided, resulting in certain data not being considered in the back analysis.

5.3.3 Sinkhole formation dynamics

Currently there is lack of good understanding around sinkhole formation dynamics. There is belief that sinkholes initiate at roof level horizon is principally a direct result of tensile failure as opposed to shear (Van Der Merwe, 1998). The failure will progress up until it intersects a competent beam in the roof. The failed material will choke up the hole. There is however no clear cut link between sinkhole caving height and the water washing effect. Water tends to wash the material at the caved material toe, thus creating more room for material failure. Un-choked areas can be exposed to the agents of weather and can further degrade thus leading to changes in the competence of the beam leading plausible collapses. The effect of water was taken into account in this research by assuming areas liable to water ingress might be problematic and were thus incorporated as high risk zones. These areas are subjected to continual recharge and discharge leading to chemical alteration and weakening of the overlying beam.

5.4 **Future work or recommendations**

This research has established a reference point for exploring other research questions. Using this report as a starting point work on a thesis investigating the clear understanding of sinkhole formation dynamics as well as numerical modelling coupled with geophysical survey methods can lead to better optimisation of the prediction model, thus leading to reduced costs as treatment could only de conducted routinely on areas where the next sinkhole has been predicted. Information in the database may be expanded to include the contribution from other mining houses lying in the same geological zone and having similar rocks types exhibiting similar characteristics. This might lead to improved correlations in managing the sinkhole prediction across the mining boundaries of mining houses. This will assist in better understanding of formation dynamics that can better equip mines to manage the risk of sinkholes in Witbank. The Witbank deposit is characterised by significant underground mining with a lot of undermined surface infrastructure. This poses a huge challenge for mining operators to maintain these large expanses of land and also acquire closure certificates when mining ceases in the Witbank coalfield.

The sinkhole database should be designed to link mines and areas exhibiting similar rock characteristics. This data should be analysed to offer a plausible sinkhole risk management solution post the Witbank deposit. Another addition which may be useful is a forum for dialogue between different mines to assist in common understanding of the sinkhole challenge facing the Witbank coal deposit. Currently work is being conducted at other sites in the group to develop prediction methodologies aligned to individual sites.

5.5 **Conclusion**

A sinkhole prediction model with enhancements of the roughening up process, drilling and blasting effectiveness was developed and implemented at site X and this system is being rolled out to other Anglo American Coal operations.

5.5.1 Key summary points

- Sinkhole prediction model was implemented at site X, and is function of the overburden depth, composition of hards in the overburden inclusive of parting thickness in the layer separating the mined seam (No.1) from the virgin (unmined No.2 seam) one. This corroborated by tier 2 critically scrutinises the physical evidence on the cloth plans as well as field information from areal flights and exposed highwalls.

- An analysis of the lithology will assist in the zonal division of areas based on rock formations, indicating areas with elevated sinkhole risk.
- Site X” should consider “Roughening up “as the primary void rehabilitation method with routine operational deployment of the TVR (TerraVision) equipment to detect residual shallow voids after roughing up and initial blasting.
- Implementation of quality of the roughening up process is crucial to ensure robust void treatment for sinkhole formation prone mining blocks, thus ensuring safe coal extraction.
- Drilling and blasting accuracy is crucial to eliminate residual sinkholes occurrence on all blasted benches.
- Proper timing between roughening up and blasting is crucial to prevent rework especially in areas liable to disturbance due to blast vibrations from distant areas.
- Precise identification of the voids seems to lie in the Ground Penetration Radar, which at this point in time is significantly limited by presence of conductive material such as clays, wet rock formations, geological anomalies and noise interference from mining equipment.

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