Safety In Mines Research Advisory Committee

Final Project Report

The impact of geotechnical factors on the secondary extraction of coal in the Witbank and Northern Highveld Coalfields, specifically related to safety

L S Jeffrey

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Executive Summary

The literature review identified geotechnical factors impacting on *unplanned* secondary coal extraction. These factors are grouped into nine broad classes of factors; namely, stratigraphy, rock /coal engineering properties, spontaneous combustion, discontinuities, igneous intrusions, collapse of previous workings, hydrology, stress environment and the primary mining parameters. It was found that for underground extraction stratigraphy, igneous intrusions, collapse of previous workings and the stress environment have the most impact on the rock mass behaviour (i.e. the roof caving and rock burst potential, rib and pillar stability, floor heave and roof / surface subsidence), roof support (both on a mine- and panel-scale) and explosions/ignitions (gas conditions, as well as spontaneous combustion). For open cast extraction the stratigraphy, igneous intrusions, collapse of previous workings, the stress environment and the primary mining parameters had greatest impact on the rock mass behaviour (slope and high wall stability and floor heave) and explosions / ignitions.

Selected collieries were then visited in order to quantify the impact the factors may have on resource/reserve estimation and safety. This resulted in the identification of additional geotechnical factors with impact on secondary extraction, as well as a tenth class of factors – secondary mining parameters. The factors impacting on safety, as well as which exploitation phase (i.e. mine planning and/or production) they affect, were identified. These factors belong to all ten classes; those with most impact are primary and secondary mining factors and stratigraphy. The collieries quantified the factors according to their impact on safety; a quantification of 10 implies the factor has a high negative impact, while a quantification of 0 implies the factor has no negative impact. The factors were evaluated considering the selection of a suitable mining method (open cast or underground) and the negative impact on underground and open cast extraction. Those impacting most on underground extraction are the sequence of pillar extraction, the competency of the roof, the caving mechanism employed, whether more than one seam is to be extracted, the secondary safety factor (before re-mining takes place), the sequence of fender extraction, whether the surface infrastructure requires to be protected or not and the condition of the pillars. The factors with greatest impact on open cast extraction are spontaneous combustion (geology, coal and mining components), standing water bodies, vertical and lateral coal quality variation and the size and geometry of the remaining reserves.

The potential impact of geotechnical factors on the classification of a deposit as a resource or reserve (according to the coal-specific portion of the SAMREC Code) was determined. It was found that certain factors *will* prevent the upgrading of a resource to reserve status (i.e.

those factors affecting the economic viability of a deposit, the reserve accessibility and reserve sterilization), while others may have a similar effect if unexpected coal losses occur during mining (e.g. factors that affect dilution, contamination and yield reduction).

In summary, standing water bodies, spontaneous combustion (the geology, coal and mining components), the competency of the roof, the condition of pillars, the time elapsed since the primary extraction, and the presence of dykes and sills are the most critical geotechnical factors in terms of safety, mining method selection, open cast and underground operations and with regard to potential adverse effects on the resource / reserve classification.

It would be misleading to present a list of factors that are critical for each operation, as every site is unique. However, this report can serve to identify which factors are *most likely* to be important and to educate individuals in the existence, effect and impact geotechnical factors can have on secondary extraction. They will then be in a position to judge which factors will be significant in that particular operation and to conduct the necessary further investigations. Chapter 9 gives further information regarding application of the findings of this report.

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1. Introduction

Geotechnical factors are defined as those characteristics of the coal seam and associated strata that impact on seam extraction, including safety. The primary and secondary geological factors (defined as syn- or post-depositional features, respectively) give rise to the first stress pattern. The mining-induced (second) stress pattern is then superimposed. Secondary extraction will further modify this composite stress pattern. Thus re-mining of previously mined areas needs to consider the interaction of three stress regimes, together with other issues such as available resources and reasons for abandonment. Several critical geotechnical factors that are important during primary extraction are also of relevance to secondary extraction. Thus critical geotechnical factors in relation to primary extraction are also considered.

A required assumption is that the area under consideration (i.e. the Witbank Coalfield) was ***not*** designed for secondary extraction. Generally, these areas are old and were mined at a time when the available machinery was not able to extract as much coal as can be extracted today or when open cast mining was not feasible, again as a result of machinery constraints. Secondary extraction is only possible where the primary extraction was by the bord-and-pillar method; it is possible either by open cast (dragline or truck-and-shovel operations) or by underground (stooping - partial or total pillar extraction) methods. The mining method chosen will depend on a variety of geotechnical factors. Where either method is suitable, the decision will become one of economics. Pillar extraction has been practised for many years in South African collieries as a means of increasing the percentage extraction. There have been many variations of the pillar extraction method, some of which have proved more successful than others. In pillar extraction, the panels consist of a bord and pillar mining layout where many pillars are created but only extracted at some later date since the panel must be developed completely before pillar extraction can commence.

This report focuses on those geotechnical factors that impact on safety and resource/reserve classification.

2. Methodology

The identification and quantification of the factors was a lengthy iterative process, achieved through continuous consultation with colliery personnel, head office representatives and additional information from international secondary extraction operations. The literature review revealed that there is no published information concerning geotechnical factors pertinent to secondary extraction, although the effects of these factors on primary extraction have been considered.

The methodology employed in this report involves six steps:

- Step 1 - identification of factors and their effects specific to the Northern Witbank-Highveld Coalfield (Table 5.1),
- Step 2 - assigning each new factor to one of the ten classes and a code within each class (Table 5.1),
- Step 3 - categorization of these factors as fixed or variable: uncontrollable or controllable during mining (Table 5.1),
- Step 4 – quantification of each factor for mining method selection, open cast and underground operations (quantifications range from 0 = low to 10 = high according to their negative impact),
- Step 5 – quantifying the impact of each factor as major, moderate or minor (major 7, 5 moderate 6.9, minor 4.9) and
- Step 6 – investigating the impact of the factors on resource/reserve classification.

The steps were addressed through consultations with geologists, mining engineers and rock engineers from collieries currently practising secondary extraction and with industry representatives experienced in stooping. A list of factors that potentially impact on secondary extraction is presented (Table 5.1). Explanatory notes to the factors are found in Appendix A. Included in the table is the class as identified in the literature review, the code for each factor, the potential impact in three different areas: geology/rock mass behaviour, mine planning and production and the fixed or variable categorization.

3. Literature review

There are two parts to the literature review – an international and a local review. The review aims at identifying critical geotechnical factors that impact on mining efficiency and safety during secondary extraction (underground and open cast). It is revealed that very little publicly available work exists with regard to secondary coal mining. However, the importance of geotechnical factors to delineate, for example, areas of distinct rock mass behaviour has been documented for other commodities, such as the South African gold mining environment (Schweitzer, *et al,* 1997).

3.1 Publicly available literature

Ellison and Thurman (1976) address the issue of geotechnical factors in a generalised form, while Fettweis (1997) deals with the specific geological factors that have geotechnical implications. Although Dunrud (1998) refers to conditions and tests that are required for primary underground extraction, these remain applicable for secondary extraction, in particular with regard to the various effects of primary extraction stresses. Ellison and Thurman (1976) suggest that the primary goal of geotechnical investigations is to:

- Outline an accurate three dimensional picture of the geology (lithology, structure and hydrology),
- Predict the interaction of geological components as related to mining and
- Design the optimum configuration to suit the chosen mining method.

According to Ellison and Thurman (1976), the ideal geotechnical investigation is such that all testing and evaluation is related directly to the issue at hand, the investigation is phased in order to allow for refinements as more information is acquired and the majority of techniques employed have multiple uses. The cost effectiveness of an investigation will be maximised when these criteria are met. Alternative techniques may be substituted where practically possible and may result in lower costs. Ellison and Thurman (op.cit.) introduced the most common mining-related geotechnical factors and ranked them for specific mine design considerations (Table 3.1; modified after Ellison and Thurman, 1976). The geotechnical factors and mining considerations are interrelated in two ways to indicate common applicability and estimated reliability of predictions. Table 3.2 (modified after Ellison and Thurman, 1976) shows the applicability of investigation techniques for various geotechnical factors.

3.1.1. Geotechnical attractiveness

Fettweis (1979) defines the geotechnical attractiveness of a raw material as the geological properties that influence the costs of exploitation (i.e. extraction and beneficiation). The factors that determine the attractiveness can be categorised according to deposit size and strata conditions (Table 3.3).

Table 3.1: The importance of geotechnical considerations specific to mining

Considerations		Underground mining																Surface mining									Surface facilities						
Geotechnical	Mining	Entries	Roof caving characteristics	Overall roof support	Local roof support	Rock burst potential	Rib and pillar stability	Subsidence	Floor heave	Washout sand channels etc.	Impact on multi-seam mining	Rippability	Transport systems	H_2O handling	Gas conditions	Monitoring system design	Spontaneous combustion	Cut slope stability	Floor heave	Spoils stability	Haul road design	Handling of water	Rippability	Rehabilitation	Monitoring system design	Spontaneous combustion	Facilities siting	Structures	Storage piles	Cut and fills	Transportation system	Impoundments, waste disposal	Spontaneous combustion
Regional geology	Geomorphology	2						2										2			2	2		2	2		2	2	2	2	2	2	
	Structural geology	2	2	2				2					2	2	2		2	2			2	2	2	2	2		2				2	2	
	Stratigraphy and lithology		2	2				2					2	2	2		2	2			2	2	2	2	2		2				2	2	
	Regional stress patterns	2	2	2		2	2	2	2		2				2		2	2	2			2					2			3		3	
Local geology	Structure	1	1	1	1	1	1	2	1	2	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	
	Stratigraphy and lithology	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
	In situ stress	1	1	1	1	1	1	1	1		2	2	2	2	2		1	1	1	1		2	2		1	1	2	2		2	2	2	
	Surficial deposits	1						1					1	2				1		1	1	1	2	1	2		1	1	1	1	1	1	1
	Nature of erosion	1	2	2	2		2	2					1					2	2	2	1	1	1	1	1		1	1	1	1	1	1	2
	Manmade alterations	1	2	2	1	1	1	1	1		2		1	1	2	1	2	1	1	2	1	1	2	1	1	2	1	1	1	1	1	1	2
Groundwater condition	Unconfined aquifers	1	2	2	2			1		2		1	1	2		2	2	1	2	1	1	1	1	1	1	2	1	1	1	1	1	1	
	Confined aquifers	1	1	1	1	2	2	1	2	1	2	1	1	1		1	2	1	1	2	2	1	2	1	1	2	1	2	2	2	1	1	2
	Aquicludes	1	1	1	1	2	2	1	2	1	2	1	1	1		1	2	1	1	2	2	1	2	2	1	2	1	2	2	2	1	1	
	Effects of fractures	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	

Key

Probability of success / Applicability	In All Areas	Often	Frequently	Occasionally	Very Seldom	2ndary Extraction
High	1	1	1	1	1	
Depends on site conditions	2	2	2	2	2	
Low	3	3	3	3	3	

Table 3.1: The importance of geotechnical considerations specific to mining (continued)

Considerations		Underground mining																Surface mining									Surface facilities						
Geotechnical / **Mining**		Entries	Roof caving characteristics	Overall roof support	Local roof support	Rock burst potential	Rib and pillar stability	Subsidence	Floor heave	Washout sand channels etc.	Impact on multi-seam mining	Rippability	Transport systems	H_2O handling	Gas conditions	Monitoring system design	Spontaneous combustion	Cut slope stability	Floor heave	Spoils stability	Haul road design	Handling of water	Rippability	Rehabilitation	Monitoring system design	Spontaneous combustion	Facilities siting	Structures	Storage piles	Cut and fills	Transportation system	Impoundments, waste disposal	Spontaneous combustion
Surface characteristics	Topography	1		2	2	2	2	1					2	2				1		1	1	1	2	1	1	2	1	1	1	1	1	1	
	Surface hydrology	1		2	2	2	2	1			2		2	1		2		1		1	1	1	1	1	1	1	1	1	1	1	1	1	2
	Erosion	1		2	2	2	2	1			2			1		2		1		1	1	1	2	1	1		1	1	1	1	1	1	
	Trafficability	1		1	2	2	2	1			2		2	1		2		1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	
	Manmade alterations	1	2	2	2	2	2	1			2		2	1	2	2		1	1	1	1	1		1	1		1	1	1	1	1	1	1
	Existing and probable developments	1	2	2	2	1	1	1			1		2	1	2	1		1	2	1	1	1		1	1		1	1	1	1	1	1	
Rock and soil properties	Resistance to weathering	1	2	2	2	3	2	2	2		2	1	1	1		1	2	1	2	1	1	1	1	1	1	2	1	1	1	1	1	1	2
	Load deformation behaviour	1	2	1	2	2	2	2	2		2			2	2	1		1	1	1	1			1	1		1	1	1	1	1	1	
	Strength	1	2	1	2	2	2	2	2		2	1	1	2	2	1	2	1	2	1	1		1	1	1		1	1	1	1	1	1	
	Time and environment dependency	1	2	1	2	2	2	2	2		2		1	1	2	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Excavation characteristics	1	2		2		1				2	1		2	2			1	2		1		1	1	1		1	1		1	1	1	
	Trafficability	1					1		1				1	1		2		1	1	1	1	1	1	1	1		1			1	1		
	Erodibility	1					2	2					1	2		2		1		1	1	1	2	1	1		1		1	1	1	1	2

Key

Probability of success / **Applicability**	**In All Areas**	**Often**	**Frequently**	**Occasionally**	**Very Seldom**	**2ndary Extraction**
High	1	1	1	1	1	
Depends on site conditions	2	2	2	2	2	
Low	3	3	3	3	3	

Table 3.2: The applicability of investigation techniques

		Surface		Sub-surface			Geophysical investigation						Field testing / instrumentation				Laboratory testing							
Geotechnical considerations	**Investigation technique**	Photogeology / remote sensing	Detailed geologic mapping	Rotary drilling	Core drilling	Geophysical Logging	Reflection	Refraction	Seismic cross hole	Electrical methods	Gravity methods	Magnetic methods	*In situ* stress	Modulus of elasticity	Groundwater monitoring	Vibration	Stress-strain	Creep	Strength	Weathering after excavation	Rippability	Geophysical	Geochemical	Soils testing
Regional geology	Geomorphology	1	1																					2
	Structural geology	1	2	2	1	2	2	2	2	2	2	2	3	3	2	3	2	3	2	2	3	3	3	2
	Stratigraphy and lithology	2	2	2	1	2	2	2	2	2	2	2	3	3	2	2	2	3	2	2	3	3	2	2
Local geology	Structure	1	1	2	1	2	2	2	2	2	2	2	2	3	2	3	2	2	2	2	3	3	3	2
	Stratigraphy and lithology	2	1	2	1	2	2	2	2	2	2	2	3	3	2	2	2	2	2	2	3	2	2	2
	In situ stress	3	2	3	2	2	3	3	2	3	3	3	1	2		2	1	2	2	2	3	3		3
	Surficial deposits	1	1	2	2	2	3	3	3	2	3	3			2	3	2	2	2			3	3	1
	Nature of erosion	1	1	2	2	3	3	3	3	3	3	3				3	3	2	2	1	2	3	2	2
	Manmade alterations	1	1	2	2	3	3	3	3	3	3	3			2	2	2	2	2	2	3	2	3	2
Groundwater conditions	Unconfined aquifers	2	2	2	1	2	2	2	2	2	2	3			1	3	2	2	2	2	3	2	2	2
	Confined aquifers	3	2	2	1	2	2	2	2	2	2	3			1	3	2	2		2	3	2	2	3
	Aquicludes	3	2	2	1	2	2	2	2	2	2	3			1	3	2	2	3	2	3	2	2	3
	Effects of fractures	2	2	2	1	2	2	2	2	2	2	3	2	3	1	2	2	2	2	2	2	2	3	3

Key

Probability of success / **Applicability**	**In All Areas**	**Often**	**Frequently**	**Occasion-ally**	**Very Seldom**	**2^{ndary} Extraction**
High	1	1	1	1	1	
Depends on site conditions	2	2	2	2	2	
Low	3	3	3	3	3	

Table 3.2: The applicability of investigation techniques for geotechnical considerations (continued)

Geotechnical considerations	Investigation technique	Surface mapping: Photogeology / remote sensing	Surface mapping: Detailed geologic mapping	Sub-surface investigation: Rotary drilling	Sub-surface investigation: Core drilling	Sub-surface investigation: Geophysical Logging	Geophysical investigation: Reflection	Geophysical investigation: Refraction	Geophysical investigation: Seismic cross hole	Geophysical investigation: Electrical methods	Geophysical investigation: Gravity methods	Geophysical investigation: Magnetic methods	Field testing/ instrumentation: *In situ* stress	Field testing/ instrumentation: Modulus of elasticity	Field testing/ instrumentation: Groundwater monitoring	Field testing/ instrumentation: Vibration	Laboratory testing: Stress-strain	Laboratory testing: Creep	Laboratory testing: Strength	Laboratory testing: Weathering after excavation	Laboratory testing: Rippability	Laboratory testing: Geophysical	Laboratory testing: Geochemical	Laboratory testing: Soils testing
Surface characteristics	Topography	1	1																	2	3			1
	Surface hydrology	2	1												2				3	2	3		3	2
	Erosion	1	1														3	2	2	2	2	2	2	2
	Trafficability	2	1													3	2	2	2	1	1	2	2	1
	Manmade alterations	1	1													2	2	2	2	2	2	3	3	1
	Existing and probable developments	1	1												2	2	2	2	2	2	2	3	2	1
Rock and soil properties	Resistance to weathering	2	2	3	1	2	2	2	2	2	3	3	2	2	2	2	3	3	3	1	3	3	2	1
	Load deformation behaviour	3	1	2	1	2	3	3	2	2	3	3	2	2		2	1	2	1	2	2	3	3	1
	Strength	3	1	2	1	2	3	3	2	3	3	3	2	2		2	1	2	1	2	2	2	2	1
	Time and environment dependency	3	2	3	2	3	3	3	3	3	3	3	2	2	2	3	2	3	3	3	3	2	2	1
	Excavation characteristics	3	2	2	2	2	3	3	2	2	3	3	2	2	1	2	2	2	2	2	1	2	2	1
	Trafficability	3	2	3	2	2	3	3	3		3	3		2	2	2	3	3	3	2	1	3	3	1
	Erodibility	2	2	2	2	2	2	3	2	2	3	3			2	2		2	2	2	2	3	2	1
	Spontaneous combustion potential	2		2	1	2	2	3		2	3	3			2								1	

Key

Probability of success \ Applicability	In All Areas	Often	Frequently	Occasionally	Very Seldom	2ndary Extraction
High	1	1	1	1	1	
Depends on site conditions	2	2	2	2	2	
Low	3	3	3	3	3	

Table 3.3: Geotechnical attractiveness

Size Factors	Strata Condition Factors
Thickness and extent (influences rock pressure)	Tectonics (large and small-scale, dip)
Depth (governs rock pressure and heat)	Extent and frequency of geological discontinuities
Regularity	Magmatic intrusions
Multiple seams	Strength of the coal and the enclosing rock
Quality characteristics	Spontaneous combustion
	Gas emission
	Nature and hydrogeological conditions of overlying strata

Seam thickness and regularity (genetic attenuation - both syn- and post-depositional) are stated to be the most important criteria. Additional geotechnical factors become important once an extraction method has been determined. For example, the stripping ratio, slope stability and hydrology are controlling factors in an open cast operation. All the above factors influence one another and are directly linked: e.g. depth and frequency of disturbance, apparent local connection between depth and methane. An important point made by Fettweis (1979) is that the change from hand-got to mechanised coal winning has greatly restricted the extractable reserves. Modern machinery has rigid limitations when considering factors such as minimum thickness, regularity and increased geological discontinuities. However, these restrictions to extractable reserves are offset somewhat by improvements in beneficiation techniques.

Initial exploration requires the determination of the extent, thickness, geometry, depth, quantity, structures and quality of coal seams. Advanced assessment focuses on geological features important for engineering and mining. These include rock and seam discontinuities, lithology, geohydrology, gas volumes, stress distribution, physical and mechanical properties of coal and the enclosing rock and the engineering properties of rocks and soils in the vicinity of potential surface facilities (Johnson *et al.*, 1986).

3.1.2. Geotechnical design - analyses and tests

Final pre-mining geotechnical design may be addressed by:

- Geological hazard analysis,
- Rock mechanics analyses,
- Physical model testing,
- Hydrologic analyses and
- Soil mechanics and foundation design analyses.

Haile and Güler (1997) subdivide the critical geotechnical parameters for South African gold and platinum deposits into five categories (Table 3.4). In coal mining, the stope width is usually referred to as the mining height and the middling thickness as the interburden thickness. Although the table refers specifically to gold and platinum, the factors are equally applicable to coal. Discussion on these factors can be obtained from the SIMRAC report. Once the critical geotechnical factors have been identified and quantified for an area, these can be used to produce plans showing areas of similar geotechnical characteristics.

Dunrud (1998) has referred to this technique as geological hazard analysis. This is a system of overlaying various maps, each showing a condition that is known to have design significance for the parameter in question, thus delineating “good” and “bad” geotechnical areas. An example given in Dunrud (1998) is roof control in underground mining where plans of coal seam floor elevation, major lineaments, areas of shallow cover, thickness of overlying channel sandstone, areas of thin shale roof below channel sandstones and areas of potentially high pore pressure in sandstone are overlain to determine a composite rated geological hazard map.

Table 3.4: Geotechnical parameters: South African gold and platinum mines

(After Haile and Güler, 1997)

Geotechnical parameter type				
Orebody geometry	**Discontinuities**	**Rock properties**	**Stress environment**	**Production parameters**
Orientation	Type: mining-induced/geological	Uniaxial compressive strength	k-ratio (horizontal: vertical strain)	Mining method
Middling thickness	Infill and contact relationship	Cohesion	Orientation of σ^1 and σ^3	Mining layout
Stoping width	Spacing Displacement Persistence/shape Orientation Zone thickness Water conditions	Friction angle Young’s modulus Poisson’s ratio		Face advance rate Span Mining direction

Rock mechanics analyses use theory to: predict the behaviour of various mining configurations; determine anticipated dimensions; evaluate various support systems; determine optimum surface slopes and establish extraction ratios. Geotechnical studies involve the study and analysis of the strength, slake durability, engineering properties and deformation characteristics of the coal and associated strata by field and laboratory testing (Dunrud, 1998). Table 3.5 details the various tests and the properties they measure.

Table 3.5: Geotechnical tests

Field Index tests		Laboratory tests	
Test	**Property**	**Test**	**Property**
Point-load strength	Tensile and compressive strength	Brazilian, pull-apart, point-load	Tensile strength
		Uniaxial, triaxial	Compressive strength
Slake durability	Resistance of clay-bearing rocks to weathering (important for roof slaking in response to air circulation with varying humidity levels)	Direct shear, Mohr's test	Shear strength
		Porosity-permeability test	Porosity-permeability
		Atterberg limits (crushed rock or soil)	Water limit boundaries
		Vicker's hardness test	Coal hardness
		Mechanical strength index	Coal strength

The engineering properties and deformation characteristics (elastic, ductile, brittle; time dependency) are determined by the elastic modulus (stress: strain), strength and stress tests and are used to classify the rock according to various engineering classifications. It should be noted that *in situ* stresses reflect the total loading history, which is determined by the vertical and horizontal stresses, together with gas outbursts. Vertical stresses are commonly approximately equal to the weight of the overburden (gravitational loading) while horizontal stresses range from 0.3 to 5.5 times the vertical stress at depths from 100 to 1000m below surface (Dunrud, 1998). Horizontal stresses are caused/influenced by:

- Gravitational loading and the effects of Poisson's ratio (horizontal: vertical strain),
- Intergranular adjustments during sedimentation, compaction and diagenesis,
- Tectonic stresses,
- Time-dependent deformation,
- Recent rapid erosion,
- Irregular mining layouts and pillar sizes, partial pillar extraction and
- Rock bursts and bumps.

Hydrologic analyses predict the volume of surface and/or groundwater and the impact of local and regional changes due to mining. Similar analyses may be performed for gas (CH_4 and/or CO_2) emission. Gas outbursts may occur in three stages:

- Rapid release of gas from cleats and fractures where high stresses occur and are exposed by mining,
- Gas explosively released from coal micro-fractures and
- Gas desorbed from pores within coal fragments.

According to Dunrud (1998) gas outbursts are more common where natural stresses are localized and may be increased by the presence of:

- Channel deposits (coal thickness and dip changes),
- Intrusives and faults due to intense localized fracturing of the coal and
- Increasing methane content (increases with depth and coal thickness).

Physical model testing can be used to predict and evaluate the relative behaviour of alternative configurations or support systems. Soil mechanics is required for site development and all surface construction. The discussion above applies mainly to primary extraction. However, it is applicable in a modified form when considering secondary extraction.

Hardman (1989) identifies two rock-engineering factors that are of importance for secondary extraction when the primary workings are close to surface (< 20 - 25 m). These are the large-scale collapse of pillars leading to a surface subsidence basin and the collapse of underground roadways and intersections due to roof failure resulting in sinkholes at the surface. Unpredictable, uncontrolled subsidence causes problems not only due to possible loss of life, but also surface sterilization and the chance of spontaneous combustion.

The possibility of collapse is influenced by a low safety factor (< 1.6), the pillar width: height ratio and the areal percentage extraction. The geotechnical factors that contribute to the collapse of roadways and intersections are:

- Geological characteristics of the overburden,
- Weathered overburden (weathered, competent strata fail as easily as unweathered, incompetent strata),
- Primary mining dimensions and
- High beam tensile and shear forces due to wider spans at intersections.

The geotechnical factors that exacerbate spontaneous combustion all cause exposure to air with resultant oxidation and self-heating of the coal. The factors are:

- Collapse of underground roadways and intersections,
- Old bord and pillar workings exposed in the high-wall of open cast operations and
- Roof fractures in shallow workings extending to surface without collapse.

Butcher, *et al* (2001) identified seam rolls, wash outs, faults, dykes and sills as having an affect on the rock mass behaviour, due to the associated jointing and potential groundwater occurrences.

3.2 The importance of geotechnical factors for secondary extraction

Several geotechnical factors (and the applicable mining considerations) are considered to be most important for secondary extraction (highlighted in Table 3.2). Only those factors that are ranked applicable in all areas with either a high success probability or a success rate dependent on site conditions are included (note also that the category for Surface Facilities has been ignored). This ranking indicates that geotechnical investigations are potentially of greater significance in underground mining scenarios, with their major contribution being in understanding the local geological conditions. The most important (i.e. with the most frequent highest ranking) geotechnical factors overall for both underground and open cast mining are:

- Stratigraphy and lithology,
- Structure,
- *In situ* stress and
- The effects of fractures on groundwater conditions.

Several investigation techniques could be useful in determining a variety of geotechnical factors, again specifically for secondary extraction (highlighted in Table 3.3). An analysis of this table shows that core drilling is the most useful technique of all, resulting in information for stratigraphy and lithology, structure, the presence of aquifers, the effects of fractures on groundwater conditions, load deformation behaviour, rock strength, excavation characteristics and the potential for spontaneous combustion. Depending on site conditions, geophysical logging appears to be the second most useful technique. This is mainly related to stratigraphy and lithology, structure and the presence of aquifers. However, detailed geological mapping, laboratory testing of soils, groundwater monitoring and stress-strain laboratory tests all have significance. Only two techniques have a high probability of success in all areas for assessing the potential for spontaneous combustion - core drilling as mentioned previously and geomechanical testing. *In situ* stresses are only measurable by field and laboratory testing. Laboratory testing of soils is only applicable for open cast mining, except around surface infrastructure for underground mines. The most important investigative techniques determining geotechnical factors in all areas (i.e. with the most frequent highest ranking) are:

- Core drilling,
- Laboratory soil testing,
- Detailed geological mapping,
- Laboratory stress-stain measurements and
- Groundwater monitoring.

Ellison and Thurman (1976) address the issue of geotechnical factors in a generalised form, while Fettweis (1979) deals with the specific geological factors that have geotechnical implications. Although Dunrud (1998) refers to conditions and tests that are required for primary underground extraction, these remain applicable for secondary extraction, in particular with regard to the various effects of primary extraction stresses. These stresses are also controlled and expressed by irregular mining layouts and pillar sizes, partial pillar extraction, rock bursts and bumps.

Few previous studies have concentrated on critical geotechnical factors of the Witbank Coalfield and their impact on mining and safety aspects. A study of this nature was therefore overdue. Ten classes of critical geotechnical factors relevant for secondary extraction have been identified as a result of this literature study (Table 3.6). These classes are related to their impact on secondary underground and open cast extraction with regard to rock mass behaviour (roof caving characteristics, rock burst potential, rib and pillar stability, floor heave, roof/surface subsidence, slope stability, high wall stability), roof support (mine- and panel-scale roof support), and explosions / ignitions (gas conditions, spontaneous combustion). A greater variety of geotechnical factors, and a more pronounced impact thereof, are suggested for underground operations, when compared with open cast mining. In addition, the classes are related according to their impact on extraction and hence safety (Table 3.7, synthesised from various sources). Inspection of Table 3.7 reveals that the largest variety of classes influence rock mass behaviour and roof support. Fewer classes impact on explosions and ignitions.

Table 3.6: Classes of geotechnical factors for secondary coal extraction

Class Number	Class description	Required parameters
1	Stratigraphy	Length, width, height, depth, dip (if > 5^0), dip direction
2	Rock / coal engineering properties	Strength, deformation characteristics, slake durability
3	Spontaneous combustion	Location, extent
4	Discontinuities	Mining-induced or geological, orientation, spacing, frequency, fill
5	Igneous intrusions	Geometry, frequency
6	Collapse of previous workings	Location, extent
7	Hydrology	Aquifers, effects of fractures
8	Stress environment*	Horizontal: vertical strain, directions of σ^1 and σ^3
9	Primary mining parameters	Initial mining method, layout, direction
10	Secondary mining parameters	New mining method, layout, direction

* Composite stress pattern after primary extraction

Table 3.7: Classes and their impact on mining

(Classes have different levels of impact, depending on whether underground or open cast mining methods are to be used during secondary extraction.)

			Underground extraction									Open cast extraction				
			Rock mass behaviour					Roof support		Explosions/ ignitions		Rock mass behaviour			Explosions/ ignitions	
Class number	**Class description**	**Category Impact**	Roof caving potential	Rock burst potential	Rib and pillar stability	Floor heaves	Roof / surface subsidence	Mine-scale roof support	Panel-scale roof support	Gas conditions	Spontaneous combustion	Slope stability	Floor heave	High wall stability	Gas conditions	Spontaneous combustion
1	Stratigraphy	F	■	■	■	■	■	■	■	■	■	■	■	■	■	■
2	Rock / coal engineering properties	F	■	■	■			■	■			■	■	■		
3	Spontaneous combustion	V								■	■				■	■
4	Discontinuities	F	■	■	■			■	■	■	■	■	■	■	■	■
5	Igneous intrusions	F	■	■	■		■	■	■	■	■	■	■	■	■	
6	Collapse of previous workings	V	■	■	■		■	■	■	■	■	■	■	■	■	■
7	Hydrology	V	■	■	■	■		■	■			■	■	■		
8	Stress environment	F / V	■	■	■	■	■	■	■		■	■	■	■		■
9	Primary mining parameters	F	■	■	■	■		■	■		■	■	■	■		■
10	Secondary mining parameters	V	■	■	■	■	■	■	■	■				■		

Shaded blocks indicate areas of impact; F = fixed (uncontrollable during mining); V = variable (controllable during mining)

4. Site visits

A limited number of collieries currently practise secondary extraction in the Northern Witbank-Highveld Coalfield. Geological and mining conditions also vary considerably between these sites. This scarcity and variability of the data must constantly be borne in mind. The following collieries were visited: Kleinkopje, Kromdraai, Arthur Taylor, Koornfontein and the Boschmanskrans Pillar Project of Douglas Colliery. In addition, the mine managers of Douglas and Delmas Collieries were also interviewed due to their extensive experience with stooping.

5. Identification and quantification of the factors

Mining house representatives (geologists, mining engineers and rock engineers) identified the factors (Table 5.1). The factors were then quantified with a view to selecting the most suitable mining method, and for open cast and underground operations as a result of the site visits. The factors are further subdivided into major, moderate and minor considering their degree of impact when selecting the most appropriate mining method or during actual secondary mining operations (Table 5.2). Factors ranked 7.0 and above are considered to have major impact; factors ranked between 5.0 and 6.9 moderate impact, while factors ranking less than 5.0 are considered to have minor impact. The impact on the mining method, open cast and underground extraction is shown in Figures 5.1 - 5.3, respectively.

Figure 5.1: Quantification of the impact on selecting a mining method

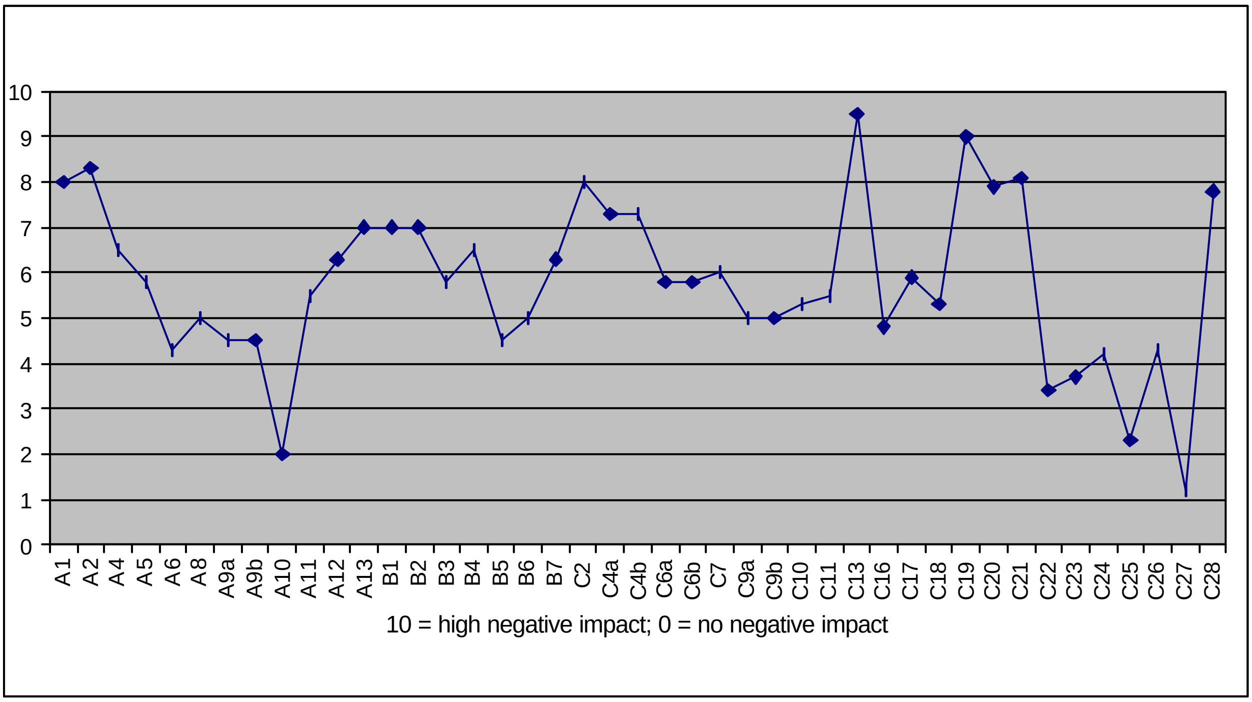


Figure 5.2: Quantification of the impact on open cast extraction

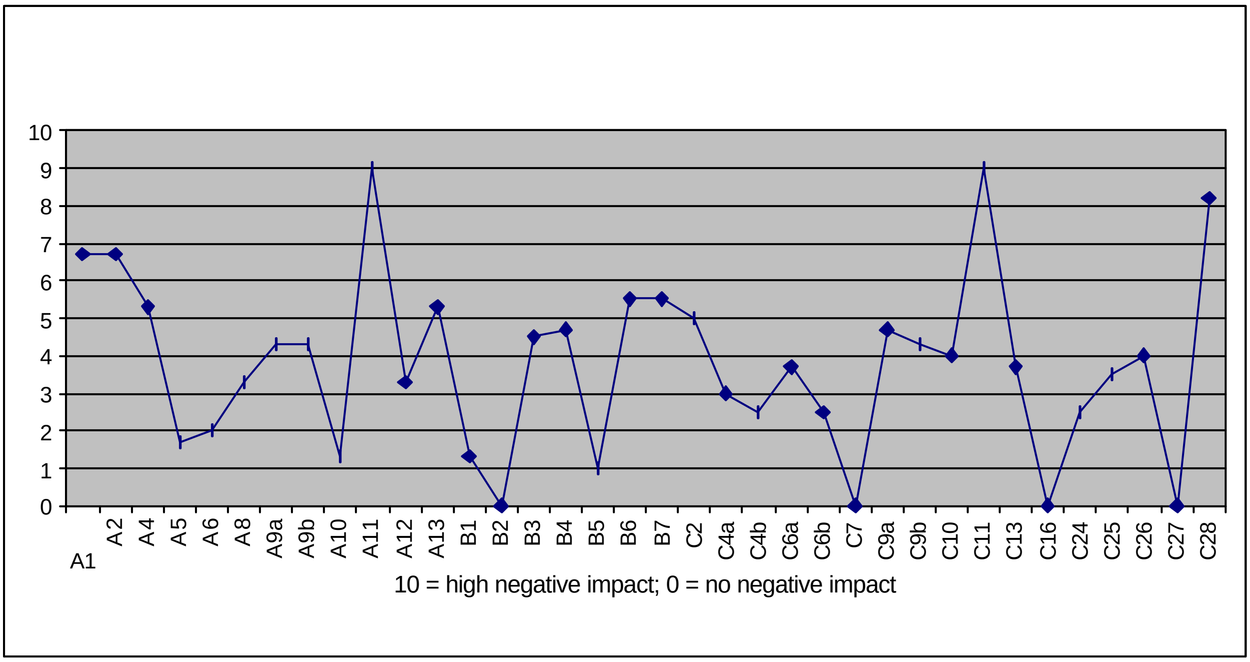


Figure 5.3: Quantification of the impact on underground extraction

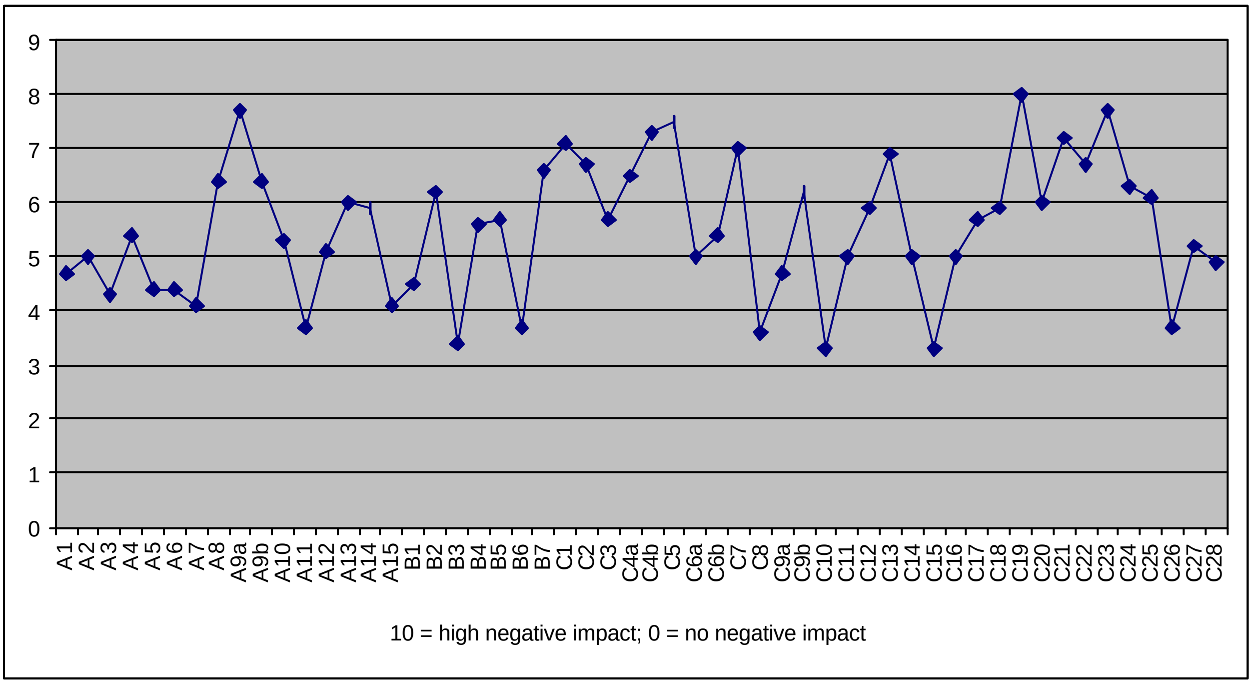


Table 5.1: Geotechnical factors impacting on secondary extraction

Class	Code	Factors	Effect: Geology/rock mass behaviour	Effect: Mine planning	Effect: Production	Sub-category
1 Stratigraphy	A1	Depth below surface	Stress regime, pillar size, support	Mining method and layout, panel, bord and pillar dimensions, percentage extraction		F1
	A2	Overburden (thickness and lithology)	Stress regime, roof stability	Mining method	Support, machinery	F1
	A3	Extractable thickness	Stress regime	Mining method and layout	Machinery, time effect	F1
	A4	Interburden (thickness and lithology)	Roof stability	Reserve sterilization, mining method	Support	F1
	A5	Seam orientation (dip, strike)	Effect of σ_H	Mining method, support patterns	Productivity, support	F1
	A6	Inseam partings and channelling (thickness and lithology)	Floor/roof undulations, roof and sidewall stability, gas outbursts*	Extraction method	Dilution, machinery	F1
	A7	Palaeotopographic variations	Seam undulations	Extraction method	Machinery, reserve losses (coal left in floor / roof)	F1
	A8	Roof discontinuities and bed forms	Roof stability	Support pattern	Support	F1
	A14	Remaining reserves (size and geometry)		Economic viability		F1
	A15	Coal quality variation (vertical and lateral)		Reserve sterilization, mining method	Machinery, coal processing	F1/V1
	B3	Differential compaction	Thickness variations, roof falls		Machinery	F1
2 Rock/coal Engineering Properties	A13	Coal strength	Pillar strength, pillar / roof stability	Mining layout, support pattern	Support	F1
	A9a	Roof competency	Pillar behaviour, roof stability	Support pattern	Machinery, contamination	F1
	A9b	Floor competency	Floor heave, pillar punching	Support pattern	Machinery, contamination	F1
3 Spontaneous Combustion	A10	Methane	Explosions	Ventilation	LOP†, ventilation (underground)	V1
	A11	Spontaneous combustion: Geology and coal component	Coal degradation (quality and strength)	Reserve sterilization	Reserve sterilization (underground), yield reduction (open cast), LOP†	F1
	C28	Spontaneous combustion: Mining component	Coal degradation (quality and strength)	Reserve sterilization	Reserve sterilization (underground), yield reduction (open cast), LOP†	V3
4 Discontinuities	B4	Faults	Seam displacement, rock mass behaviour, pillar strength, roof stability, gas outbursts*	Mining layout, direction of pillar splitting, sequence of pillar extraction, overall mining direction	LOP†, overall mining direction, sequence of pillar extraction, direction of pillar splitting, support	F1
	B5	Joints	Rock mass behaviour, pillar strength, roof stability, gas outbursts*	Mining layout	Mining direction	F1
5 Igneous Intrusions	B1	Dykes	Devolatilization, seam displacement, rock mass behaviour, gas outbursts*	Reserve sterilization, mining method and layout	Reserve accessibility, LOP†, support	F1
	B2	Sills	Devolatilization, seam displacement, rock mass behaviour, gas outbursts*	Reserve sterilization, mining method and layout	Reserve accessibility, LOP†, support	F1

Table 5.1: Geotechnical factors impacting on secondary extraction (continued)

Class	Code	Factors	Effect			Sub-category
			Geology/rock mass behaviour	Mine planning	Production	
6 Collapse of workings	B6	Sinkholes	Promotes spontaneous combustion	Reserve sterilization	Rehandling, safety (men and machines)	V1
	B7	Surface subsidence (general)	Rock mass behaviour, promotes spontaneous combustion	Reserve sterilization, mining method	Safety (men and machines)	V1
7 Hydrology	A12	Aquifers	Stability	Reserve sterilization	Flooding, reserve sterilization, LOP†, AMD‡ (pumping, treating)	V1
	C11	Standing water bodies	AMD‡, spontaneous combustion	Reserve sterilization	Flooding, reserve sterilization, LOP†, AMD‡ (pumping, treating)	V2
	C26	Seepage water	Stability		Pumping, LOP†, support	V3
8 Stress environment	C9a	Primary mining-induced discontinuities and stresses (including macro-fracturing)	Stress regime	Mining layout	Support	F2
	C9b	Secondary mining-induced discontinuities and stresses (including macro-fracturing)	Stress regime	Mining layout	Support	F3
	C10	Slope stability (open cast)	High wall failure	Reserve sterilization		V2
	C25	Horizontal stress	Stress regime	Mining direction and layout, support	Support	F3
9 Primary mining parameters	C7	Pillar condition	Poor condition reduces primary safety factor	Support	Support, LOP†, reserve sterilization	F2
	C8	Previous access		May restrict planned access		F2
	C2	Primary mining method and equipment	Stress regime, roof / pillar condition	New pillar size/orientation	Mining direction, percentage extraction, machinery	F2
	C3	Mining history		Mining method and layout, overall mining direction, economic viability		F2
	C12	Adjacent panels (extracted or not)	Stress regime, overall mining direction	Mining layout, sequence of pillar extraction	Extraction sequence, accessibility	F2
	C13	Time since primary extraction	Pillar decay, thus roof stability, sinkholes, surface stability	Support, reserve sterilization	Support, reserve sterilization, LOP†	F2
	C16	Panel width	Stress regime, pillar load, surface stability, caving mechanism	Support	Support	F2
	C17	New pillar width	Stress regime	Safety factor	Support, loading, production	F2
	C18	New bord width	Stress regime	Safety factor, support pattern	Support	F2
	C14	Previous backfilling	Stress regime	Extraction time (productivity)	Dilution	F2
	C27	Coal ply in roof	May prevent roof falls in incompetent roof areas, dilution	Mining method, support	Support	V2
	C4a	Primary safety factor		Mining method, support, machinery	Extractability, support, machinery	F2
	C6a	Primary mining height	Stress regime, stiffness of pillars, safety factor	Mining method	Machinery, increased cutting time	F2

Table 5.1: Geotechnical factors impacting on secondary extraction (continued)

Class	Code	Factors	Effect			Sub-category
			Geology / rock mass behaviour	**Mine planning**	**Production**	
10 Secondary mining parameters	C15	Overall mining direction	Stress regime	Mining layout, sequence of pillar extraction	Sequence of pillar extraction	V3
	C19	Sequence of pillar extraction	Stress regime	Mining direction, support	Support	V3
	C20	Direction of pillar splitting	Stress regime	Support	Support	V3
	C21	Sequence of fender extraction	Stress regime	Support	Support	V3
	C22	Snook size	Stress regime	Support	Support, time of extraction	V3
	C23	Caving mechanism	Stress regime	Support pattern	Support	V3
	C24	Extraction technique	Surface stability	Full / partial extraction, reserve sterilization	Support	V3
	C5	Multi-seam extraction	Stress regime	Mining method and layout, pillar superimposition, sequence of seam extraction	Sequence of seam and pillar extraction	V3
	C1	Surface infrastructure		Reserve sterilization		V3
	C4b	Secondary safety factor (before mining)		Mining method, support, machinery	Extractability, support, machinery	F3
	C6b	Secondary mining height (before mining)	Stress regime, stiffness of pillars, safety factor	Mining method	Machinery, increased cutting time	F3

* Due to coal fracturing
† Loss of production
‡ Acid mine drainage

Table 5.2: Factors with major impact

	Factors with major impact	Class	Quantification
Mining method selection	Remaining reserves (size and geometry)	1	10.0
	Surface infrastructure	10	10.0
	Time since primary extraction	9	9.5
	Overburden (thickness and lithology)	1	8.3
	Depth below surface	1	8.0
	Extractable thickness	1	8.0
	Primary mining method and equipment	9	8.0
	Mining history	9	8.0
	Multi-seam extraction	10	7.5
	Adjacent panels	9	7.5
	Primary safety factor	9	7.3
	Coal strength	2	7.0
	Dykes	5	7.0
	Sills	5	7.0
Open cast extraction	Spontaneous combustion: Geology and coal component	3	9.0
	Standing water bodies	7	9.0
	Spontaneous combustion: Mining component	3	8.0
	Coal quality variation (vertical and lateral)	1	7.3
	Remaining reserves (size and geometry)	1	7.0
Underground extraction	Sequence of pillar extraction	10	8.0
	Roof competency	2	7.7
	Caving mechanism	10	7.7
	Multi-seam extraction	10	7.5
	Secondary safety factor (before mining)	10	7.3
	Sequence of fender extraction	10	7.2
	Surface infrastructure	10	5.7 – 7.1
	Pillar condition	9	7.0

6. Impact of geotechnical factors on safety

The factors identified during site visits as having impact on various aspects of safety are detailed in Tables 6.1 – 6.5. The factors were also classified into sub-categories according to whether the factor is controllable or not during mining (i.e. variable or fixed) and to their origin (geology, primary extraction or secondary extraction).

Table 6.1: Factors impacting on safety

Class	Code	Factors	Effect			Sub-category
			Geology/rock mass behaviour	Mine planning	Production	
1 Stratigraphy	A1	Depth below surface	Support			F1
	A2	Overburden (thickness and lithology)	Roof stability		Support	F1
	A4	Interburden (thickness and lithology)	Roof stability		Support	F1
	A5	Seam orientation (dip, strike)			Support	F1
	A6	Inseam partings and channelling (thickness and lithology)	Gas outbursts*			F1
	A8	Roof discontinuities and bed forms	Roof stability		Support	F1
	B3	Differential compaction	Roof falls			F1
2 Rock/coal Engineering Properties	A13	Coal strength	Pillar strength, pillar / roof stability		Support	F1
	A9a	Roof competency	Pillar behaviour, roof stability			F1
	A9b	Floor competency	Pillar punching			F1
3 Spontaneous Combustion	A10	Methane	Explosions and fire	Ventilation	Ventilation (underground); fire control; loss of life; injury	V1
	A11	Spontaneous combustion: Geology and coal component	Fire			
	C28	Spontaneous combustion: Mining component				
4 Discontinuities	B4	Faults	Pillar strength, roof stability, gas outbursts*		Support	F1
	B5	Joints				
5 Igneous Intrusions	B1	Dykes	Gas outbursts*		Support	F1
	B2	Sills				
6 Collapse of workings	B6	Sinkholes	Promote spontaneous combustion		Safety (men and machines)	V1
	B7	Surface subsidence (general)				
7 Hydrology	A12	Aquifers	Stability		Flooding	V1
	C11	Standing water bodies	Spontaneous combustion			V2
	C26	Seepage water	Stability		Support	V3
8 Stress environment	C9a	Primary mining-induced discontinuities and stresses (including macro-fracturing)			Support	F2
	C9b	Secondary mining-induced discontinuities and stresses (including macro-fracturing)			Support	F3
	C10	Slope stability (open cast)	High wall failure			V2
	C25	Horizontal stress		Support	Support	F3

Table 6.1: Factors impacting on safety (continued)

Class	Code	Factors	Effect			Sub-category
			Geology/rock mass behaviour	Mine planning	Production	
	C7	Pillar condition	Poor condition reduces primary safety factor	Support	Support	F2
	C2	Primary mining method and equipment	Roof / pillar condition			F2
9 Primary mining parameters	C13	Time since primary extraction	Pillar decay, thus roof stability, sinkholes, surface stability	Support	Support	F2
	C16	Panel width		Support	Support	F2
	C17	New pillar width		Safety factor	Support	F2
	C18	New bord width		Safety factor, support pattern	Support	F2
	C27	Coal ply in roof	May prevent roof falls in incompetent roof areas	Support	Support	V2
	C4a	Primary safety factor		Support	Support	F2
	C6a	Primary mining height	Safety factor			F2
10 Secondary mining parameters	C19	Sequence of pillar extraction		Support	Support	V3
	C20	Direction of pillar splitting		Support	Support	V3
	C21	Sequence of fender extraction		Support	Support	V3
	C22	Snook size		Support	Support	V3
	C23	Caving mechanism			Support	V3
	C24	Extraction technique	Surface stability		Support	V3
	C4b	Secondary safety factor (before mining)		Support	Support	F3
	C6b	Secondary mining height (before mining)	Safety factor			F3

Notes:

* Gas outbursts due to coal fracturing;

† Spontaneous combustion is also classed as a mining factor; it is partly a function of the nature of the coal and associated carbonaceous sediments and is generally *triggered* by mining activities;

F Fixed subcategory (uncontrollable during mining);

V Variable subcategory (controllable during mining);

1 Geological factor;

2 Primary mining factor;

3 Secondary mining factor.

Table 6.2: Factors impacting on support

Class	Code	Factor	Exploitation phase		Sub-category
			Mine planning	Product-ion	
Stratigraphy	A1	Depth below surface		X	F1
	A2	Overburden (thickness and lithology)		X	
	A4	Interburden (thickness and lithology)		X	
	A5	Seam orientation (dip, strike)		X	
	A8	Roof discontinuities and bed forms		X	
Rock/coal eng. properties	A13	Coal strength		X	F1
Discontinuities	B4	Faults		X	F1
	B5	Joints		X	
Igneous intrusions	B1	Dykes		X	F1
	B2	Sills		X	
Hydrology	C26	Seepage water		X	V3
Stress environment	C9a	Primary mining-induced discontinuities and stresses		X	F2
	C9b	Secondary mining-induced discontinuities and stresses		X	F3
	C25	Horizontal stress	X	X	
Primary mining parameters	C7	Pillar condition	X	X	F2
	C13	Time since primary extraction	X	X	
	C16	Panel width	X	X	
	C17	New pillar width		X	
	C18	New bord width		X	
	C27	Coal ply in roof	X	X	V2
	C4a	Primary safety factor	X	X	F2
Secondary mining parameters	C19	Sequence of pillar extraction	X	X	V3
	C20	Direction of pillar splitting	X	X	
	C21	Sequence of fender extraction	X	X	
	C22	Snook size	X	X	
	C23	Caving mechanism		X	
	C24	Extraction technique		X	
	C4b	Secondary safety factor (before mining)	X	X	F3

Notes:

X Exploitation phase of impact
F Fixed (uncontrollable during mining)
V Variable (controllable during mining)
1 Geological factor 2 Primary mining factor 3 Secondary mining factor

Table 6.3: Factors impacting on spontaneous combustion/gas/explosions

Class	Code	Factors	Type	Exploitation phase	Sub-category
				Production	
Stratigraphy	A6	Inseam partings and channelling	Gas outbursts*	X	F1
Spontaneous combustion †	A10	Methane	Explosions	X	V1
	A11	Geology and coal component	Fire	X	F1
	C28	Mining component		X	V3
Discontinuities	B4 B5	Faults Joints	Gas outbursts*	X X	F1
Igneous intrusions	B1 B2	Dykes Sills	Gas outbursts*	X X	F1
Collapse of workings	B6 B7	Sinkholes Surface subsidence (general)	Promote spontaneous combustion	X X	V1
Hydrology	C11	Standing water bodies	Spontaneous combustion	X	V2

Table 6.4: Effect of factors impacting on stability

Class	Code	Factors	Type of stability	Exploitation phase		Sub-category
				Mine planning	Product-ion	
Stratigraphy	A2 A4 A8 B3	Overburden Interburden Roof discontinuities Differential compaction	Roof	X X	 X X	F1
Rock/coal eng. properties	A13 A9a	Coal strength Roof competency	Pillar/roof Roof	X X	X X	F1
Discontinuities	B4 B5	Faults Joints	Roof	X X	X X	F1
Collapse of workings	B7	Surface subsidence	Surface	X	X	V1
Hydrology	A12 C26	Aquifers Seepage water	Roof	X	X X	V1 V3
Stress environment	C10	Slope stability	High wall	X	X	V2
Primary mining parameters	C7 C13 C27	Pillar condition Time since primary extraction Coal ply in roof	Pillar/roof Roof/surface Roof	X X X	X X	F2 V2
Secondary mining parameters	C24	Extraction technique	Surface	X	X	V3

Notes for both tables:

* Gas outbursts due to coal fracturing

† Spontaneous combustion is also classed as a mining factor; it is partly a function of the nature of the coal and associated carbonaceous sediments and is generally *triggered* by mining activities

X Exploitation phase of impact

F Fixed (uncontrollable during mining)

V Variable (controllable during mining)

1 Geological factor 2 Primary mining factor 3 Secondary mining factor

Table 6.5: Factors impacting on other safety aspects

Class	Code	Factors	Type	Exploitation phase		Sub-category
				Mine planning	Production	
Rock/coal engineering properties	A13	Coal strength	Pillar strength		X	F1
	A9b	Floor competency	Pillar punching		X	
Discontinuities	B4	Faults	Pillar strength	X	X	F1
	B5	Joints		X	X	
Hydrology	A12	Aquifers	Flooding	X	X	V1
	C11	Standing water bodies		X	X	V2
Primary mining parameters	C2	Primary mining method and equipment	Roof/pillar condition	X	X	F2
	C17	New pillar width	Safety factor	X	X	
	C18	New bord width		X	X	
	C6a	Primary mining height		X	X	
Secondary mining parameters	C6b	Secondary mining height (before mining)	Safety factor	X	X	F3

Notes:
X Exploitation phase of impact
F Fixed (uncontrollable during mining)
V Variable (controllable during mining)
1 Geological factor 2 Primary mining factor 3 Secondary mining factor

7. Impact of geotechnical factors on resource/reserve classification

The impact on the resource / reserve classification, for both opencast and underground operations, was established (Table 7.1). Factors that will prevent the upgrading of a resource to a reserve impact on the economic viability of the deposit, the sterilization of the resource and the accessibility of the resource. Other factors that may prevent the upgrading of the resource to reserve status affect coal losses during extraction: dilution, contamination, coal left in the roof or floor and yield reduction through quality degradation by spontaneous combustion.

Table 7.1: Factors impacting on the resource/reserve classification

Potential impact	Dependant variable	Factors	Code
Will prevent upgrading a resource to a reserve	Economic viability	Remaining reserves (size and geometry)	A14
		Mining history	C3
	Reserve sterilization	Interburden (thickness and lithology)	A4
		Coal quality variation (vertical and lateral)	A15
		Spontaneous combustion: Geology and coal component	A11
		Mining component	C28
		Dykes	B1
		Sills	B2
		Sinkholes	B6
		Surface subsidence (general)	B7
		Aquifers	A12
		Standing water bodies	C11
		Slope stability (open cast)	C10
		Pillar condition	C7
		Time since primary extraction	C13
		Extraction technique	C24
		Surface infrastructure	C1
	Reserve accessibility	Dykes	B1
		Sills	B2
		Adjacent panels (extracted or not)	C12
May prevent upgrading a resource to a reserve, if unforeseen conditions encountered	Dilution	Inseam partings and channelling	A6
		Previous backfilling	C14
		Coal ply in roof	C27
	Coal left in floor/ roof	Palaeotopographic variations	A7
	Contamination	Roof competency	A9a
		Floor competency	A9b
	Yield reduction (spontaneous combustion)	Geology and coal component	A11
		Mining component	C28

8. Findings

The factors impacting on safety, mining method selection, the mining operation (open cast or underground) and on the resource / reserve classification are shown in Table 8.1.

In summary, those factors that are critical for safety reasons are also important with regard to the financial feasibility of any secondary coal extraction operation. Geotechnical factors affecting safety can have major monetary implications, potentially far beyond that of any actions required to prevent the risk and / or restore the mining environment after a safety-related incident has occurred.

Table 8.1: Common factors

	Factor	**Classification impact**
Open cast operations	Standing water bodies	Reserve sterilization
	Spontaneous combustion: Geology and coal component	Reserve sterilization and yield reduction
	Spontaneous combustion: Mining component	Economic viability
Underground operations	Roof competency	Contamination
	Pillar condition	Reserve sterilization
Mining method selection	Dykes Sills	Reserve accessibility and sterilization
	Time since primary extraction Spontaneous combustion: Mining component	Reserve sterilization

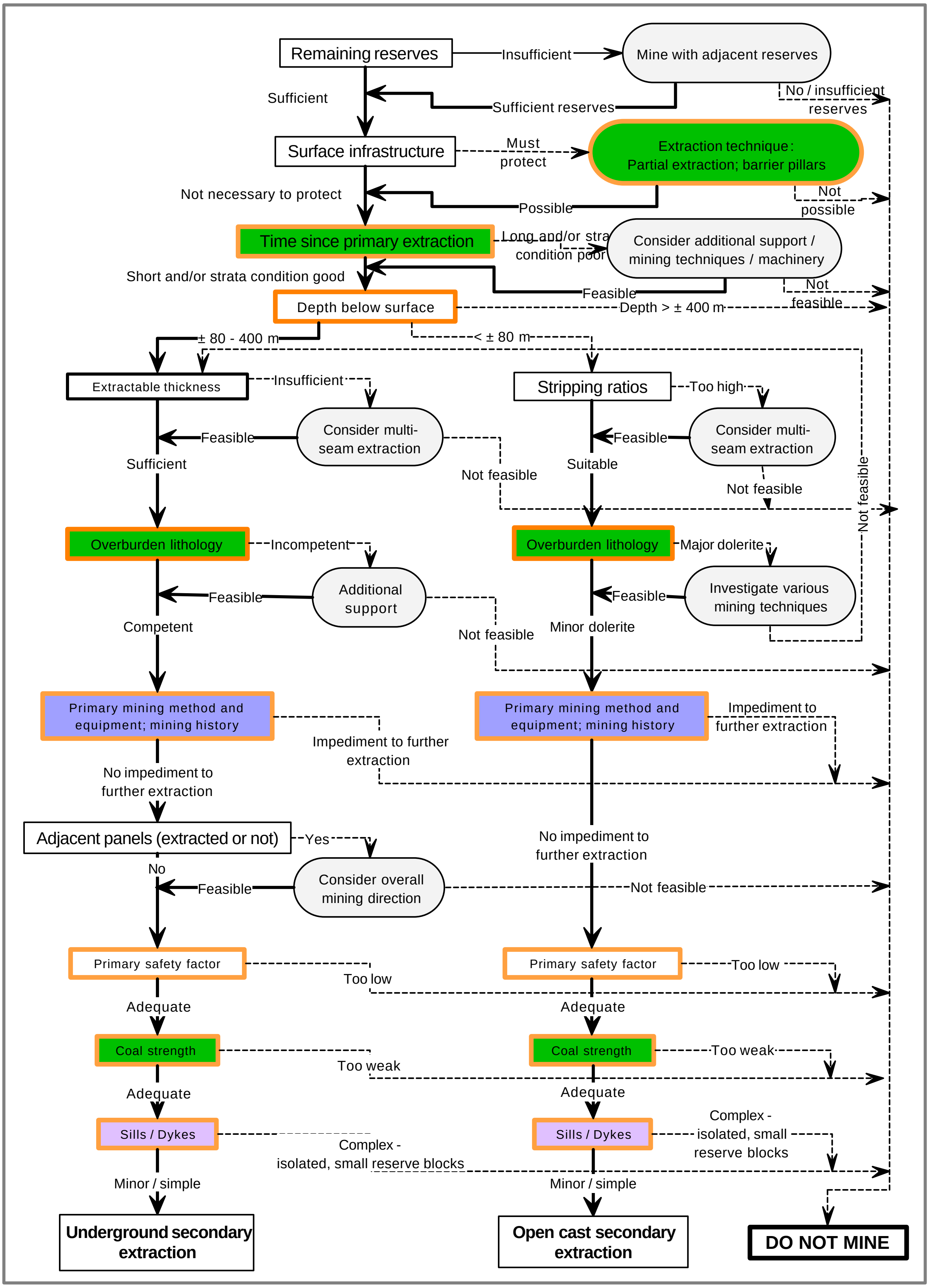
9. Application

As each secondary extraction site is unique, it is not possible to identify a list of factors that will be significant at every site. However, this report can serve to sensitise personnel to which factors are *most likely* to be important. The information contained herein, particularly the tables, can then be used as a guide to investigate further.

It is suggested that particular attention be paid to those areas of Tables 3.1 and 3.2 that are highlighted (indicating applicability to secondary extraction) with a number 1 in the largest font. These are the aspects of critical importance to secondary extraction. Table 5.1 can be used to familiarise the user with the potential effects a factor may have, and in which area those effects may manifest themselves. This will provide forewarning of what to expect if a particular factor is present. Table 5.2 shows those factors that should be considered at every site, as they are those most likely to have impact in the majority of sites. Table 6.1 is similar to Table 5.1, except that it deals with the effects on safety only. It is important that these effects should be well understood before exploitation occurs. Tables 6.2 – 6.5 simply provide further detail on the factors in Table 6.1. The presence or absence of the factors identified in the tables should be ascertained, and their possible impact assessed, before extraction occurs.

Figures 9.1 – 9.3 show the potential impact geotechnical factors may have when selecting a suitable mining method, or during open cast or underground secondary extraction. The diagrams have been colour-coded to indicate those factors that have specific impact on the safety of the operation. These can be referred to when considering secondary extraction.

It must be stressed that this report *does not* provide a methodology to be applied in every case of secondary extraction. As each site is unique, the most that can be done is to educate individuals as to what effect a factor can have in order to allow timeous identification of important factors and provide suggestions as which factors are most likely to be critical.



Key:
Fill = Rock mass behaviour

Border = Production

Stability | Roof/ pillar condition | Gas | Support

Figure 9.1: Potential impact on mining method selection

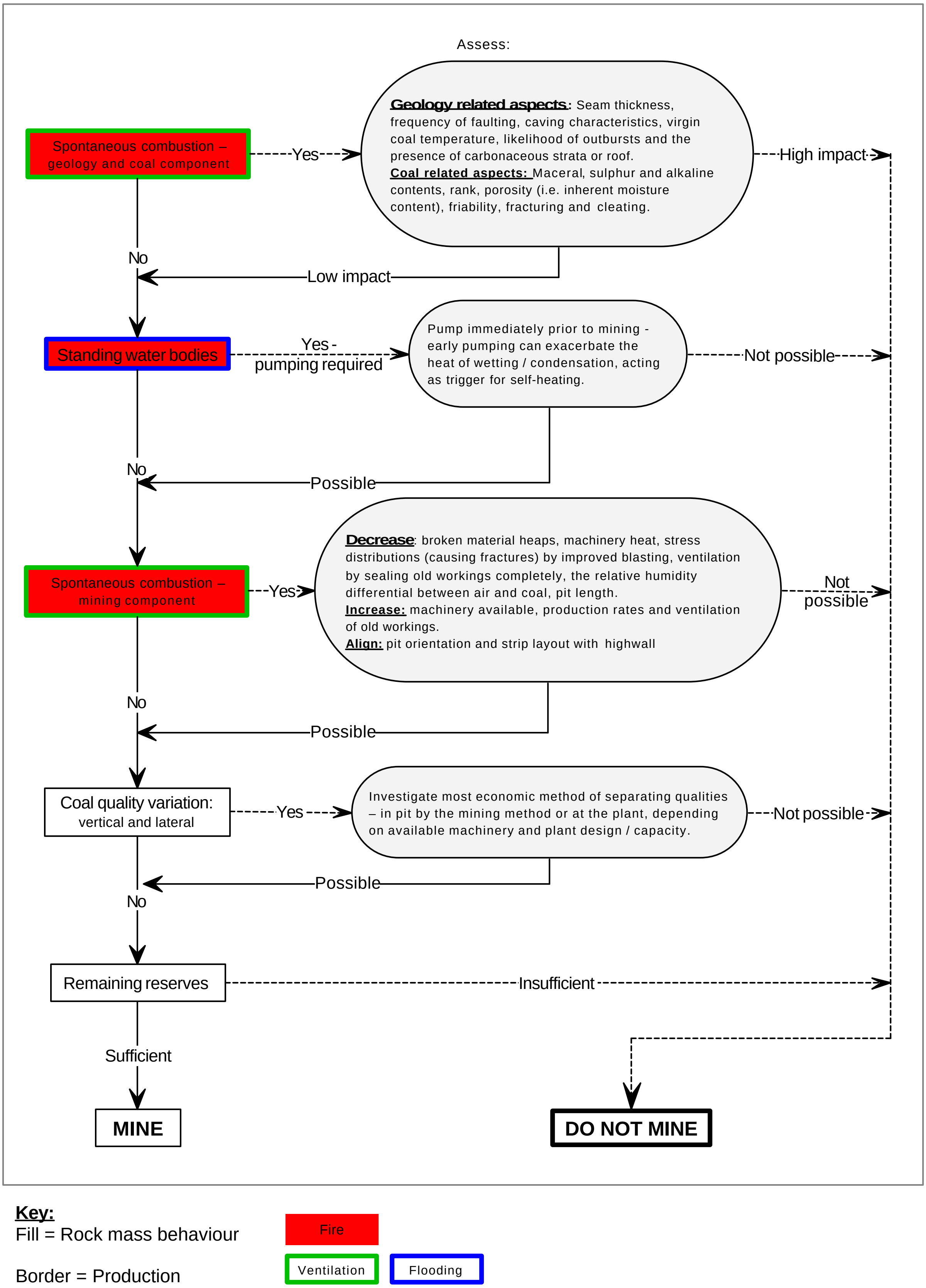
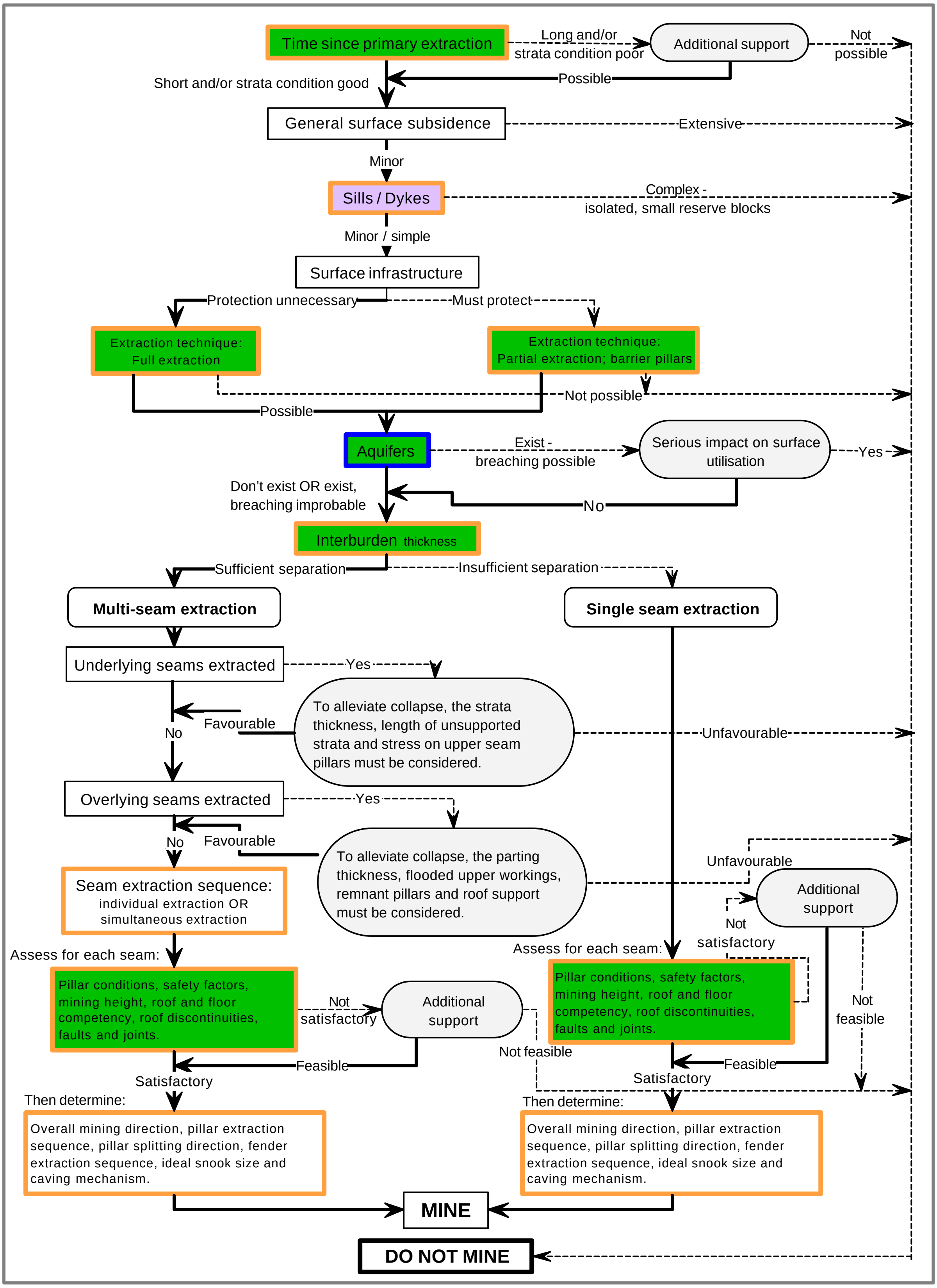


Figure 9.2: Potential impact on open cast extraction



Key:
Fill = Rock mass behaviour — Stability, Gas
Border = Production — Support, Flooding

Figure 9.3: Potential impact on underground extraction

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APPENDIX A - Explanatory notes for some of the factors

Class 1: Stratigraphy

Depth below surface (code A1, sub-category F1)

Stooping in South Africa currently operates optimally between 40 and 250 m below surface, where the effect of depth on the stooping operation is minimal; at depths outside this range the impact increases. The maximum depth at which stooping is viable may increase in the future. Longwalling (a total extraction method) can be economically practised at greater depths, but this technique is not considered in this investigation.

Overburden thickness and lithology (code A2, sub-category F1)

The competency of the immediate overburden is important. Thick, massive sandstones or moderate to thick dolerite sills are usually competent, while silt- or mudstones, cross-bedded sandstones, and sandstones inter-bedded with silt- and/or mudstones are generally incompetent. Providing the overlying strata are competent, the impact is quantified as 5 (moderate).

Extractable thickness (code A3, sub-category F1)

The total thickness of coal that can be extracted impacts on the stripping ratios and thus becomes an economic factor. The currently accepted South African minimum extractable thickness is ~ 1.2 m. However, thinner seams are extracted in other parts of the world, notably Europe. Stooping is most suitable where the seam thickness is 1.2 - 4 m (using continuous miners), but is also dependent on the equipment available. The impact is quantified as 2 (minor) in the optimal thickness range. Where seams are thicker, primary extraction of a select horizon could be by longwall extraction, or by top or bottom coaling, leaving pillars that could then be extracted by stooping.

Interburden thickness and lithology (code A4, sub-category F1)

Assuming that multi-seam extraction has been practised during the primary mining, an interburden thickness of 0 - 15 m has major impact on stooping (impact = 9); in this case, pillars of overlying seams must be superimposed to assure stability of the strata. Thickness greater than 15 m poses little problem and is quantified as 1 (minor). If the interburden between two potentially extractable seams is very thin (< 1 m), the strength of the parting between them becomes critical. This impacts on the method of extraction of the seams, the equipment used and the blasting techniques employed, both for an open cast operation and for stooping.

Seam orientation (code A5, sub-category F1)

Dips in most South African coalfields (excluding the Soutpansberg field) are generally low. In such cases, the impact is minor. However, if dips exceed 3 , stooping is excluded and the impact of the seam orientation rises to major (10).

Thickness and lithology of in-seam partings and channelling (code A6, sub-category F1)

The thickness and strength of in-seam partings controls their extractability. Partings with strengths ~ 90 MPa cannot be extracted owing to machinery constraints; thick partings can likewise not be extracted. A continuum from thin, strong partings to thick, weak partings has major impact on the extractability (8 and greater), while thin, weak partings have minor impact. Thick, weak partings also increase contamination.

Palaeotopographic variations (code A7, sub-category F1)

When present and of significant amplitude and frequency, the impact of variations in the palaeotopography is high (7 - 8), particularly when present in the floor. These undulations impact on the machinery suitable for extraction, as well as the rate of extraction. Production delays may result in premature goafing, endangering lives, machinery and productivity.

Roof discontinuities and bed forms (code A8, sub-category F1)

In general the impact is moderate (5 - 6), but is dependant on correct support during both primary and secondary extraction to provide effective management of roof conditions. Roof bolt installation once support problems have been encountered is not effective, as bed separation would already have occurred in the overlying strata (Beukes, 1992). The angle at which the discontinuity, whether major or minor, crosses the bord or roadway is of great importance. Discontinuities parallel to the length of the bord are more critical and difficult to support than perpendicular discontinuities. Adequate support is thus decisive in preventing failure. Pillar failure transfers stresses to the remaining pillars, thus increasing their load and possibly exceeding their design strength. Further failure and loss of reserves (and possibly also workers and machinery) may result.

Size and geometry of remaining reserves (code A14, sub-category F1)

The impact of the remaining reserves on the secondary extraction is dependent on the size of the reserves, together with the equipment available. Where reserves are small and little equipment is available, the impact is major (10); however, if equipment is available the impact can vary from minor through to major. Large reserves with little available equipment have similar impact ranges (i.e. 0 - 10), while the impact on large reserves with plentiful available equipment is minor.

Class 2: Rock / coal engineering properties

Coal strength (code A13, sub-category F1)

Coal strengths affect the time that elapses before pillars crush. If coal strengths are low, pillars may crush ahead of the stooping operation. This causes the extraction rate to drop, increasing the extraction time. This may result in premature pillar collapse. Coal strengths that are either too low or too high have major impact on stooping and both result in premature failure of the pillars and supported strata. Numerous coal strength tests have been performed on Witbank and Highveld coals.

Roof competency (code A9a, sub-category F1)

The lithology and discontinuities of the immediate roof rock govern its competency and hence the support required. Although contamination may occur and machinery may get stuck, poor roof conditions can generally be managed. Comments made regarding roof discontinuities and bed forms apply equally here. The impact is considered moderate.

Floor competency (code A9b, sub-category F1)

Poor floor competency tends to have greater negative impact than poor roof competency. Floor heave, reduced pillar safety factors and pillar punching can result. Floor heave is attributed to three reasons (Beukes, 1992): high horizontal stresses where the floor fails in tension, high vertical stresses where pillar punching results and swelling rocks (containing clay minerals) in the floor strata. Remnant pillars in lower mined seams cause stress concentrations that will be transferred to the upper seam workings. This may be observed as pillar spalling or floor heave.

Class 3: Spontaneous combustion

Methane (code A10, sub-category V1)

The impact of methane in underground collieries is extremely high as satisfactory ventilation of the goaf is almost impossible. Thus build-up of methane can occur until explosive concentrations are reached, often with tragic results. In open cast secondary extraction operations the impact of methane is low as it is continuously vented to the atmosphere and rarely reaches explosive concentrations.

Spontaneous combustion (code A11, sub-category F1 and code C28, sub-category V3)

Spontaneous combustion has been divided according to two factors: spontaneous combustion arising owing to the nature of the geology and the coal itself and spontaneous combustion due to mining practices. That due to the geology and the coal is fixed, as nothing can be done to ameliorate it, while that due to mining can be controlled by adapting the mining practices. Little research appears to have been done by industry on its effect on coal qualities and yields, resulting in reserve loss. Although significant, it does not appear to prevent mining. At worst it causes production delays as preventative measures must be undertaken, additional costs associated with these measures are incurred and logically the product yields must be reduced. Of the three Anglo Coal open cast secondary extraction operations (Kleinkopje, Kromdraai and New Vaal), all three are experiencing problems with spontaneous combustion, although that at Kleinkopje is very recent (October 1999). It would seem that spontaneous combustion *will* occur at some stage; a method or technology to prevent self-ignition long enough to allow mining is required. Ceasing mining operations is not a solution; the only permanent solution currently known is total extraction. The burning collieries around Witbank are not only a safety and pollution hazard, but also threaten the Maputo Development Corridor, as the main rail link to Mozambique passes through the area and is surrounded by these old, burning collieries. If methane occurs in explosive concentrations the possibility of ignition reaches dangerous proportions and a colliery may have to be closed (e.g. Lidell and Blair Atholl collieries in Australia). Fortunately South African collieries are not particularly gassy. Spontaneous combustion is dealt with in greater detail in Section 5.3.

Class 4: Discontinuities

Faults (code B4, sub-category F1) and joints (code B5, sub-category F1)

Faults with large throws (order of tens of metres) are largely absent in the Witbank-Highveld Coalfield. Minor faulting of less than 2 m is found, but has minor impact on the extraction. Jointing can however, have major impact on both open cast and underground operations. Ideally pillar sides should not be parallel to joint sets as spalling is more likely to occur. The direction of advance should be perpendicular to the major joint direction.

Class 5: Igneous intrusions

Dykes (code B1, sub-category F1) and sills (code B2, sub-category F1)

The impact of dykes and sills on the mining operation is low to moderate, depending on the thickness and frequency of intrusion and the amount of devolatilization present. Thin dykes have often been found to cause greater devolatilization than thicker dykes. The heat of intrusion also reduces the coal strength. During stooping operations, the row of pillars containing the dyke is usually not extracted. Sills overlying the seam may have increased the strength of the roof lithologies due to the baking effect, thus having a positive impact on extraction. These will determine whether an area can be accessed by open cast methods. Areas overlain by a sill are usually not accessible by open cast operations, as are areas of intense dyke intrusion. The low ranking of these features is thus a result of the open cast operations being in areas of few intrusions. I would suggest that intrusives are extremely important, probably having a ranking of around 8. There appears to be a connection between the intensity of intrusion and the presence of methane, more methane being found in areas of intense intrusion. Methane will assume significance only in areas where it is present in explosive concentrations or where there is spontaneous combustion. Dykes and sills in underground operations govern the accessibility of reserves. Loss of reserves may occur as a result of burning and the development layout may be affected, particularly where the coal has been displaced by the intrusion. This will lead to production delays and increased development costs. The rock mass behaviour may be adversely affected and a different mining method may need to be employed. Reserve sterilisation will occur where reserve blocks are rendered inaccessible by the intrusions.

Coal strength (class 5, code A13, subcategory F1)
The coal strength influences the strength and condition of pillars, roofs and sidewalls.

Class 6: Collapse of workings

Sinkholes (code B6, sub-category V1)
The size and frequency of sinkholes will have varying impact on the secondary extraction. Only one site visited had serious subsidence problems (Kromdraai). In areas where subsidence is extensive, such as the state-owned mines around Witbank (Transvaal and Delagoa Bay, Middelburg Steam, etc.), the importance of sinkholes and unstable ground will increase. The unstable ground may cause a change in machinery requirements (e.g. using draglines rather than trucks and shovels, using special explosives that are less viscous and can be pumped over longer distances thus keeping explosives vehicles away from dangerous ground). Different blasting techniques (such as buffer blasting) may be effective in certain cases to close voids. Any remedial actions required will at the very least result in production delays, although it is unlikely that mining will be prevented.

Class 7: Hydrology

Aquifers (code A12, sub-category V1)
Breaching of aquifers should be avoided whenever possible, particularly in terms of the environmental problems associated with these. Minor aquifers have little impact on mining,

only requiring additional pumping to reduce volumes. Breaching of major aquifers may cause flooding of the workings, with possible loss of life and machines, or even flooding of the entire mine. The impact of such an occurrence is extremely high. Breaching of aquifers may result in flooding of the mine (or portions thereof), together with depletion of water boreholes. Although these factors may not cause abandonment, they will have an impact in terms of remediation costs and delayed production.

Standing water bodies (code C11, sub-category V2)

Small amounts of water will have minimal effect on mining, while large volumes will have major impact on both open cast and stooping operations. The entire reserve may be lost owing to sudden, rapid influx of water. At a minimum, production delays and pumping costs will be incurred. Besides the logistics and cost, dewatering of old bord and pillar panels allows air ingress to the previously sealed workings. Oxidation will begin, increasing the likelihood of spontaneous combustion. Acid mine drainage may become a problem, requiring expensive remediation measures. Dewatering also removes the support the water has lent to the pillars, which in time may lead to pillar spalling, roof collapse and sinkhole formation. The water may also act as a lubricant along joints and fractures promoting failure.

Seepage water (code C26, sub-category V3)

Any discontinuity, whether structural (fault planes), depositional (contacts between different lithologies) or mining induced (fractures), may act as a conduit for seepage water, thus decreasing the competency of such discontinuities and increasing the chance of catastrophic failure.

Class 8: Stress environment

Horizontal stress (code C25, sub-category F3)

Stresses are due to the confinement of the rock mass and unloading as a result of erosion. The effects of horizontal stresses are seen in pillar spalling and failure along poorly supported discontinuities.

Class 9: Primary mining parameters

Pillar condition (code C7, sub-category F2)

Where pillars have deteriorated with time, the initial safety factor is reduced and the coal strength factor must be adjusted accordingly. This will only be important where the pillars are weak; collapse may occur if pillars are required to bear heavy loads. This factor will probably not operate in isolation, but will be linked with others such as final primary safety factors, the competency of the roof and floor, any discontinuities within the pillars and the strength of the coal itself. Pillars in coal that has been mined by drill and blast methods tend to be more fractured and prone to spalling than where mined with continuous miners. Cracking, scaling and roof-pillar fractures are common. However, with time the condition of the pillars mined with continuous miners approaches that of the drill and blast pillars (pers. comm., N. van der Merwe).

New pillar width (code C17, sub-category F2)
Narrow pillars will have major impact on stooping while broader pillars will have moderate impact.

New bord width (code C18, sub-category F2)
Roof collapse and support problems are likely to be experienced where bord widths are greater than approximately seven metres.

Coal in the roof (code C27, sub-category V2)
Leaving a thin skin of coal in the roof can help prevent roof falls, thus reducing contamination of the remaining reserves.

Class 10: Secondary mining parameters
Secondary safety factor (code C4b, sub-category F3)
This needs to be calculated once the appropriate measurements have been taken.

Sequence of fender extraction (code C21, sub-category V3)
The order of extraction should be from the goaf towards the solid.

Multi-seam extraction (code C5, sub-category V3)
The majority of collieries mine more than one seam, which should be taken into consideration during the design stage. The underground extraction of one seam may affect the subsequent mining of another seam if the seams are in close proximity. This is due to subsidence and stress concentrations, which can result in difficult mining conditions The extraction sequence should be from top seam to bottom seam(s) for strata control purposes. However, marketing constraints and coal quality variation make it difficult to mine in descending seam order. In the Witbank area multi-seam bord and pillar mining is common and several combinations of mining multiple seams have been tried in the Natal coalfields. The potential safety hazard associated with different multi-seam mining sequences and extraction methods (Hill, 1994) is shown (Table A1).

Table A1: Potential safety hazards in multi-seam mining layouts
(after Hill, 1994)

Method of Mining		Safety Hazard
Upper Seam	Lower Seam	
Bord & pillar	Bord & pillar	Spalling on pillars and parting collapse if the interburden is thin and there is no superimposition.
Pillar extraction (2)	Bord & pillar (1)	Roof falls in lower seam, parting collapse if interburden is thin.
Bord & pillar (2)	High extraction (1)	Tensile zones and spalling in upper seam when mining over goaf/solid boundary, floor collapse over incomplete goafs. High safety risk if Parting:height ratio low.
Remnant pillar (1)	Bord & pillar (2)	Intersection collapse in lower seam when mining under remnant.
Pillar extraction (1)	Pillar extraction (1)	Simultaneous mining in both seams - roof falls in lower seam.
High extraction (1)	High extraction (2)	Preferred method of mining except where remnant pillars and water exist.

Note: Figures in brackets refer to the sequence of seam extraction

The feasibility of multi-seam extraction is also dependent on the nature and thickness of the interburden, plus whether sufficient reserves remain at suitable depths. For example, the interburden between two seams may be such that mining of the lower seam is precluded, or the seam may be of insufficient thickness to warrant exploitation. Like the extractable thickness, multi-seam extraction impacts on the stripping ratios in open cast operations. It affects the mining method, mining layout, the superimposition of pillars and the sequence of seam extraction in underground operations.

Overall mining direction (code C15, sub-category V3)

In horizontally disposed seams, the direction of mining has minor impact on the stooping. However, in areas where the seams have pronounced dip, the impact is moderate to major. The direction of stooping should occur away from low-lying areas where water collection can occur and away from previously mined panels. Wherever possible, mining between two goafed panels should be avoided; where not possible, extraction should be from the oldest panel towards the youngest. The extraction direction should be constant in order to distribute the load evenly to the adjacent unmined pillars. The resultant micro-cracks in the roof and surrounding pillars will then have the same orientation and pattern as the existent stress contours. Changing the direction of stooping will change the directions of the stress contours, leading to the development of a new set of micro-cracks crosscutting the pre-existing ones; this may cause severe undesirable strata instability.

Surface Infrastructure (code C1, subcategory V2)

Surface infrastructure becomes less significant with increasing depth below surface, or if the overlying strata are sufficiently competent to support the overburden.

Direction of splitting (codeC20, sub-category V3)

Pillars should always be split in the direction of overall mining (into the main goaf), ensuring that the main pillar fractures develop parallel to the goaf. The fender closest to the goaf will be weakened by these fractures when a pillar is split parallel to the goaf.

Extraction technique (codeC24, sub-category V3)

Partial high extraction mining, (by partially extracting all pillars or by total extraction of some pillars, leaving others *in situ* - chequer board extraction) is sometimes unavoidable in order to prevent subsidence of the overlying strata. According to Canbulat (2000), the design principles for partial high extraction methods are complicated. The stiffness of both the pillars and the overburden strata must be determined. The system stiffness must be greater than the pillar stiffness for the partial high extraction layouts to be safe (i.e. failure is in a controlled manner). The pillar width:height ratio falls within the range of non-violent failure at lower mining heights where the panel width becomes less important; it is therefore more efficient to employ chequer board pillar extraction. Protecting the overburden beams from failure by restricting panel widths, predominantly controls partial high extraction at higher mining heights where it is more efficient to split all pillars while restricting panel width.

Snook size (code C22, sub-category V3)

In pillar extraction, the aim is to remove all pillars completely. However, this is always difficult to achieve. Snooks or even whole pillars will be left behind. Therefore, the "correct size" snooks should be left to protect the pillars and control the stresses on the pillars still to be extracted.

APPENDIX B - Description and rationale of the nominal terms

Category – a set of factors with similar possibility of control during mining. There are two categories:

- Category F – fixed: the mining operation has no control over these factors, which dictate the rock mass behaviour.
- Category V – variable: some control is feasible over the variable factors. These factors may modify, rather than dictate, the rock mass behaviour.

Class – a set of factors of common type. The ten classes (1 to 10) are defined in Table 2.2. Factors can belong to the same class, but different groups, e.g. aquifers and standing water bodies both belong to class 7 (hydrology), but aquifers are part of group A (primary geological factors) as they are a result of the geology of the deposit, while standing water bodies are classified as group C (mining factors) because they are controlled by the inflow of water into the old workings. Similarly, factors can belong to the same group, but different classes. An example of this is the final safety factor from the primary extraction (class 7 – primary mining parameters) and mining induced discontinuities and stresses (class 8 – stress environment), which both belong to group C (mining factors) as they are a result of the previous mining.

Code – a unique identifier for each factor, based on the group into which it falls. Thus group A factors are labelled A1 through to A14, etc. The numeric part of the code does *not* imply any hierarchy within the factors.

Dependant variables – the aspects of secondary extraction affected by the factors.

Factor - those characteristics of the coal seam and associated strata that impact on seam extraction, including safety.

Group – a set of factors with similar origin. The groups are:

- Group A: primary geological factors – owing to syn-depositional geological features,
- Group B: secondary geological factors - resulting from post-depositional geological features and
- Group C: mining factors – arising from the primary extraction.

Subcategories – categories F and V are divided into two subcategories each:

- Subcategory F1 - those factors present before mining commenced. They are an intrinsic component of the rock mass, and control its behaviour to a very large degree. All primary and secondary geological factors (bar methane, spontaneous combustion, aquifers and sinkholes) belong to this subcategory.
- Subcategory F2 – factors arising from the primary extraction. Since mining has ceased, no changes are possible.
- Subcategory V1 - primary and secondary geological factors to which some remedial measures can be applied.
- Subcategory V2 - mining factors that can be controlled during secondary extraction.

CSIR: MINING TECHNOLOGY

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CLIENT ADDRESS:	Private Bag X 63 Braamfontein 2017				
TEL NUMBER:	(011) 358 9180	FAX NUMBER:	(011) 403 1821		

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The impact of geotechnical factors on the secondary extraction of coal in the Witbank and northern Highveld coalfields, specifically related to safety.
(Final project report)

MEMBER OF STAFF / AUTHOR OF REPORT:	L. S. Jeffrey

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DR R G GÜRTUNCA
Divisional Director
CSIR: Mining Technology
P O Box 91230
Auckland Park
2000

Fax No.: (011) 726-7308
Tel No.: (011) 358-0072