A geotechnical rationale for the design of South African open cast coal mine highwalls

by R.J. Butcher*

Introduction

Open cast mining in South Africa has grown and developed rapidly since its introduction in the mid-1970s when first Optimun and then Arnot collieries commenced open cast operations. Today there are eight large open cast mines employing in the region of twenty draglines. Open cast mining was motivated mainly by the availability of shallow-lying coal seams under ideal geotechnical conditions. However, in the past decade, following the exhaustion of the traditional South African coal fields, highwall rockfall hazards have increased with the deterioration of ground conditions as mining has progressed into weaker geotechnical areas.

A further aspect that relates to the recent concern surrounding highwall instability is the maturing nature of the South African open cast coal industry. In essence there has been a substantial change in the nature of the industry from total extraction of virgin coal seams to a situation where a significant number of mines are extracting old underground pillars. In geotechnical terms, the impact of this shift to pillar mining is that open cast operations are now conducted under more complex conditions, including increased groundwater regimes, subsidence due to pillar instability and greater depths of weathered overburdens. In this respect, given the continuous exhaustion of the higher grade export coal reserves, it is expected that pillar mining by open cast methods will become more widespread.

The above changes have resulted in the need for a greater geotechnical input being required to maintain safe highwall conditions.

Open cast highwall design trends

Observations from a highwall stability research project (Butcher et al. 2001) established that the following aspects were applicable in terms of mining practice in First World coal mining countries.

➤ Geotechnical design rather than reactive cleaning methods primarily address highwall instability problems.

➤ Highwall geometries (heights, bench widths, etc.) and orientations can adequately be designed through the use of standard slope stability design methods.

➤ The appropriate highwall design requires a geotechnical assessment of both the overburden and interburden soil rock mass of the mining lease area.

➤ A highwall can be divided into two main geotechnical areas: the soft soil/weathered rock mass and the hard rock mass (over/mid burden). Design of the soft soil mass highwall is to be carried out in accordance with the standard soil slope principles, while the hard rock mass (over/inter burden) is to be designed in accordance with standard rock slope design principles.

➤ Open cast mines can be geotechnical classified into two main types:

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- Open (conventional) wall open cast highwalls
- Open cast mines using buffer blasted highwalls.

- Open (conventional) highwalls—classic soil and rock slope failure of the overburden and interburden.
- Open cast mines using buffer blasted highwalls—highwall subsidence due to pillar/bord collapse or minor buffer slope sloughing.

The research project further indicated that, where excessive soft overburdens occur, spontaneous combustion problems exist, where highwall pillar extraction is to be carried out, a buffer blasted highwall has to be used.

Open cast mining techniques can be further sub-divided into those operations where draglines are used and those that make use of truck and shovel methods (Figure 1; Butcher et al. 2001). Draglines are used under more competent geotechnical conditions, while truck and shovel methods are used in soft rock conditions or where more complex geotechnical conditions exist (Runge 1981). The project also showed that different geotechnical highwall hazards exist for the two main types of open cast mines.

The above findings indicate that appropriate geotechnical design techniques are the primary test in controlling highwall failure, and that highwalls can be successfully designed through the application of standard slope stability design techniques. The information required for such designs can be corrected by carrying out a standard geotechnical site investigation (geotechnical assessment) of the highwall soil and rock mass.

From a geotechnical aspect the level of input with respect to field investigation and geotechnical design increases as the mining method flexibility or rock/soil mass strength decreases. In practical terms, once an open cast mine is in steady state operation, little or no flexibility exists to change highwall geometries or mining directions. Panel lengths can be increased, reduced, or coal can be lost. However, such changes have a severe impact in terms of pit economics. Therefore open cast mine design should be correct in terms of geotechnical practice, or otherwise an increased risk of highwall failure has to be accepted. The implication of the above statements is that open cast highwalls require greater levels of geotechnical design input, compared to other surface operations, due to their inherent lack of flexibility (with additional geotechnical work being required for truck and shovel operations).

Observations, by Butcher et al. (2001), show that although a number of mines have world class slope (rock fall hazard) management programmes, most highwalls in South African mines were designed according to local experience, with little or no standard geotechnical input. An area of concern is the overall scarcity of mine geotechnical plans. The absence of such information results in the changes in ground conditions across the mining lease area not being identified and the subsequent re-activation of recurring geotechnical problems. The practical implications of a lack of geotechnical mine plans are as follows:

- Global strip mining project stability cannot be assessed. This may lead to concerns being raised by financial institutions regarding the project, potential risks, and economic viability
- The most appropriate open cast mining method cannot be determined

- The risk of box cut highwall collapse is increased as these excavations may be sited and orientated in the most unstable ground conditions
- Stable highwall geometries and maximum wall heights cannot be determined
- Strip mining orientation cannot be determined
- Incidents of highwall collapse may increase due to the presence of excessive weathered or jointed overburdens/midburdens. This may lead to coal loss or reduced production rates

- The conversion of open (conventional) highwalls to buffer blasted slopes due to the presence of excessive soft/weathered overburdens in the highwall. This may lead to production loss due to the need to establish the buffer
- Areas of increased risk subsidence due to the failure of weak or weathered strata above old bord-and-pillar workings which cannot be identified
- Areas of pillar collapse areas cannot be pro-actively identified
- Geotechnical hazard areas cannot be pro-actively identified.

The above points highlight the importance of integrating geotechnical engineering into open cast mine design.

The majority of First World coal producing countries considered it necessary to carry out some form of geotechnical assessment and design to ensure excavation stability during mining. The author’s observations would appear to affirm that countries such as Australia, the United Kingdom and the United States have higher on-mine geotechnical standards than is the norm in South Africa. In saying this it is important to realize that the coal mining industries of the abovementioned countries have traditionally not operated under such optimal geotechnical conditions as in South Africa. In addition, the close proximity of dwellings, roads and other structures has resulted in a greater awareness of the importance of excavation stability in the First World countries. This awareness has been increased through an abundance of experienced engineers and geologists in these countries, who are actively involved with open cast mining. In contrast, South Africa has suffered a skills shortage of such professionals for many years. Despite a wealth of technical information pertaining to pit slope design, the lack of mine awareness has been compounded by the fact that little or no recent literature is readily available which deals directly with highwall stability.

Consequently, it is important to have a clear

![Figure 1—Geotechnical classification of strip mining methods (after Butcher et al. 2000)](image-url)
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understanding of the aims and principles that surround highwall design before the formulation of a geotechnical rationale can be possible.

Highwall design rationale aims, principles and criteria

The primary aim of the design rationale is the reduction of highwall failures by the implementation of appropriate design criteria. Geotechnical site investigations and analyses are therefore aimed at determining the following:

➤ The anticipated ground conditions (geotechnical domain) at the site of the proposed open cast mine
➤ The most favourable open cast mining orientation in terms of highwall stability
➤ The maximum highwall height and face angle
➤ Overall highwall geometry (height and width of highwalls and benches) with respect to multi-seam mining.

When considering the above aims, cognizance must be taken of the main cost advantage that open cast mining enjoys over underground methods. This advantage is due to the favourable economies of scale afforded by the use of draglines and steeply inclined highwalls. In many cases the use of such equipment, in weak or complex geological conditions, results in a situation where a certain amount of rock mass failure has to be tolerated. However, if the scale and frequency of such failures compromises the economic viability of the operation or the safety of personnel, it may become necessary to change to a more appropriate mining method such as truck and shovel mining. It is therefore necessary to be able to set design principles as a guide to mining method selection and highwall design.

To this end highwall design principles were originally proposed by Steffen and Moss (1978), and subsequently extended by Butcher et al. (2001). The 5 proposed highwall design principles are listed below:

➤ Highwall rock fall hazard reduction must be pro-actively focused on geotechnical design
➤ Geotechnical design must take cognizance of the type of open cast mining operation to be employed (i.e. is pillar extraction to be undertaken)
➤ Geotechnical design must limit failure without compromising economics
➤ Should highwall failure occur, it must not involve primary movers (i.e. draglines). Excavate the steepest possible highwall with primary movers. These units should be situated as close as possible to the highwall to reduce rehandle
➤ Where local highwall failure has been determined, a cleaning strategy must be implemented to combat rock fall hazards.

When considering the aims and principles in relation to the discussed highwall design trend, observed in First World countries, criteria for open cast mine highwall design can be determined. In this regard, highwall design rationale criteria must encompass:

➤ An assessment of geotechnical conditions using standard soil and rock slope investigation methods
➤ A method of determining whether a conventional open or buffer blasted highwall should be used

➤ A method whereby the highwall geometry and orientation can be determined using standard slope engineering design principles.

Geotechnical rationale for highwall design

An overview of a highwall design rationale is given in Figure 2. The overview has been based on the discussed design trends, aims, principles and criteria. The design rationale can be divided into two main sections, namely:

➤ An overall assessment of strip mine geotechnical conditions
➤ Highwall design.

An overall assessment of strip mine geotechnical conditions

The idea behind the overall assessment of geotechnical conditions is the characterization of the geological and mining environment across the mining lease area. The aim of this evaluation is:

➤ The determination of highwall geotechnical design parameters
➤ The construction of a mine geotechnical domain model
➤ The determination of the most appropriate mining method for the prevailing geotechnical conditions (i.e. conventional open or buffer blasted highwalls).

The overall geotechnical assessment is further subdivided as shown below.

Geotechnical site investigation

A standard geotechnical slope stability site investigation of the mining lease area. The geotechnical investigation is to focus on the two geotechnical domains which comprise the highwall, these being the:

➤ Soft soil overburden where fieldwork normally includes the drilling or excavation of trial pits, auger holes, shafts and diamond and/or percussion drill holes. Experience in South Africa has shown that two auger holes per kilometre are required to facilitate representative disturbed soil sampling. Rosengren (1981) has also stated that one geotechnical borehole per 2 km, or 15% of geological boreholes, should be geotechnically logged. All soil horizons exposed in auger holes and from boreholes should be profiled. Auger hole refusal depths should be noted, soil grading tests, Atterberg Limits and soil shear strengths tests must be conducted. From this information the relative heights and strengths of the soft soil highwall, across the mining area, can be ascertained, safe designs determined, adjusted and compiled.

➤ Hard rock over/interburden, where fieldwork is aimed at determining the rock mass strength of the hard overburden/interburden. This work involves the determining of the compressive/shear strengths, highwall structural regime and rock mass classification values of the respective lithological units. In addition the macro-geological structures (position and orientation of major faults, dykes, rolls, and washout, etc.) and the ground/surface water regimes also need to be established and form part of the design input. The above data can be obtained by the following
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- Laboratory testing of recovered drill cores
- Rock mass classification of highwall exposures and the logging of recovered drill cores
- Highwall joint surveys
- Borehole core orientation for joint orientations
- Identification of major structural trends from geological plans and aerial photographs
- Identification of major structural trends from satellite images
- Determination of ground/surface water flow trends from hydrological/hydrogeological surveys.

As in the case of the soft overburden, the relative heights and strengths of the hard rock over/interburden can be ascertained across the mining area, safe designs determined, adjusted and compiled.

One of the outputs from the geotechnical site investigation would be the construction of a **geotechnical domain model of the mining lease area.** In essence this is a model from which geotechnical plans and sections can be compiled as the model incorporates all the abovementioned geotechnical data.

Such models are essential if geotechnical programmes are to be pro-active, as the anticipated ground conditions and structural regimes in the mining block need to be known in the initial open cast planning stages. This is due to the fact that little or no flexibility exists to change highwall orientations, geometries, face angles, and mining methods/equipment once in steady state operation. In many cases mining companies undertake detailed geotechnical design work for the siting of the box-cuts, but neglect to extend such work across the mining block. This may result in the box-cut being positioned in the most competent ground, but orientated in the worst possible direction. This could result in future highwall stability problems.

The following information is normally required to construct a geotechnical domain model:

- Coal seam contours
- The position of major structural features (fault, dykes etc.)
- A rosette diagram showing the major structural trends
- Major structural strike directions
- Areas of excessive soft overburden
- Schematic stratigraphic column showing the different geological horizons, with assigned shear strengths, classification values and structural characteristics
- Direction of the maximum principal stress and areas of suspected stress-related damage
- Existing workings (surface and underground)
- Large bodies of water, rivers, pans and streams
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- Subsidence areas
- Groundwater flow patterns.

Butcher et al. (2001) found that most mines have sufficient data to construct a geotechnical domain model. The information can generally be located from rock engineering and geological reports, geological plans, section reports, environmental management programme reports and mine groundwater reports.

**Mining geotechnical investigations**

Open cast mining over the past two decades has shown that the highwall geometry cannot be based purely on geotechnical, mining equipment or geological considerations (Butcher et al. 2001). Certain geotechnical mining conditions exist in which buffer blasted highwalls must be used to ensure safety and stability. South African experience has shown that buffer blasted highwalls are to be used under the following conditions:

- Where the soft-to-hard overburden ratio exceeds 1:1
- Where spontaneous combustion of coal seams has occurred
- Where open cast mining is undertaken in highly jointed rock masses and pre-splitting cannot achieve safe highwalls
- Where horizontal stress regimes may cause excessive highwall instability
- Where a ventilation seal has to be formed during underground pillar extraction to prevent spontaneous combustion
- Where subsidence and crown hole failure from lower pillar workings may occur, affecting open cast mining operations.

South African experience has also shown that determining the potential for spontaneous combustion potential of the coal (Falcon 1985), the compilation of hard-to-soft overburden ratio plans and determining the potential for underground coal pillar extraction is required to define the mining method, and hence the highwall geometry before detailed geotechnical design work can be undertaken.

A study should be undertaken to determine the stability of pillars and bords safety factors across the mining area. In this respect it may also be prudent to construct contour plans of pillars/bords to determine hazard areas. (Rigby and Haines 1980, Foure 1987, and Butcher et al. 2001).

Smooth wall blasting and pre-splitting techniques are primary tools in the prevention of rockfalls once steady state operations begin. Research (Anon 1995, Butcher et al. 2001) indicates that pre-splitting becomes ineffective under the following conditions:

- In blocky rock masses
- Where joint spacing is < 5 m apart
- Where joints cross the pre-split line between 15° to 45°
- Where joints have trace lengths > 5 m
- In soft weathered rock mass conditions.

Consequently, it becomes important to conduct a geotechnical blasting assessment to determine the effects of different rock mass conditions on blast designs. In this respect the following aspects are of importance:

- The geotechnical characteristics of the overburden that relate to the powder factor determination
- The strength and density of the rockmass as well as variations rating which influences the choice of high shock energy or high heave energy explosives
- The stand-up time of blast holes to reduce back break damage as a result of collapsed hole overburdens
- The structural characteristics of the highwall relating to effective pre-splitting.

**Highwall design**

As stated previously, there are two types of highwall, namely open (conventional) highwalls and buffer blasted highwalls. In geotechnical terms the design of open highwalls and a pit is similar. The stability and subsidence of the buffer slope are the main technical issues that need to be addressed with respect to buffer blasted highwalls. A brief description of the design methodology for these two types of highwall is given below.

**Open highwalls**

The design procedures for both dragline and truck and shovel operations can be considered similar to those for an open pit. The main aspects that need to be determined are summarized here.

**The orientation of the highwall**

To determine the correct orientation of the highwall it is necessary to determine the major structure trend across the mining block. This can be done using the geotechnical rose diagram. Taking stability considerations into account, the highwalls can then orientated according to the rules given by McCracken (1981), which state that:

- Where one joint set is present in a rock mass, the ideal highwall orientation is perpendicular to the strike of the joint set.
- Where two joint sets are present, the highwall should be cut so as to bisect the larger angle of the intersection between the two joints sets.

In applying these rules to the typical structural regimes found in the South African coal fields, Butcher et al. (2001) found that the above rules have to be strictly adhered to, to maintain highwall stability.

**Highwall geometry**

It is essential to determine the maximum highwall height, face angle and bench width. In practical terms where multi-seams are extracted, highwalls are separated by a 30 m to 40 m wide bench (determined from practical mining considerations), situated at the floor elevation of the uppermost seam. Therefore in geotechnical design each individual highwall may be considered to represent a large bench. The following methods are used to facilitate the design.

- **Empirical methods**—these are generally used to scope the overall highwall geometry and are based on practical experience. Soil slope charts have also been produced by numerous researchers (Bishop and Bjerum 1960). However, the most convenient methods are those developed by Hoek and Bray (1981). The design of a truck and shovel operation is similar to that of an open pit as it comprises a series of benches (stacks) between the seams. Haines and Terbrugge (1991) developed a design chart which is used to...
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determine stack angles based on Laubscher’s Mining Rock Mass Rating system. Butcher et al. (2001) modified the above graph for dragline operations. However, it must be understood that these methods are for preliminary design use only. These graphs are shown in Figures 3 and 4.

➤ *Deterministic methods*—these methods are used to determine the stability of a slope by determining the factor of safety of either the rock/soil mass or wedges formed by joints within the slope. A recent development is the use of computer programmes to calculate factors of safety.

➤ *Probabilistic techniques*—using deterministic methods, input parameters are specified with the resultant output being a factor of safety. In reality, it must be understood that the input parameters used in highwall analyses are subject to considerable variation. In such cases, it is more prudent to determine the probability of failure rather than a single factor of safety.

Buffer blasted highwalls

Two geotechnical design considerations exist for this type of highwall:

Design of the buffer slope

In reality the slope angle is formed by the angle of repose of the thrown buffer. Therefore buffer slopes are generally stable with a slope angle of 60° to 70°. However, due to blast material compaction/variation, the presence of soft overburdens and pore water pressures failures may occur. It should also be noted that during overburden removal buffer slope angles in excess of 70° can occur. Therefore to ensure safety, it is necessary to determine the maximum possible slope angles and heights. This can be achieved through analysing the buffer as a soil slope, using empirical and deterministic techniques. Input parameters are determined from laboratory tests, blast fragmentation analysis, observations or physical modelling.

Subsidence analysis

In a pillar extraction situation subsidence, by either bord or pillar failure, affects operations in the following manner:

➤ Subsidence of the highwall crest posing a threat to both personnel and equipment
➤ Subsidence immediately ahead of the buffer which poses a threat to drilling equipment
➤ Subsidesces in the vicinity of highwall which poses a threat to both haul roads and personnel.

![Figure 3—Design chart to determine slope angles using MRMR classification data (after Haines and Terbrugge, 1991)](image)
In practical terms, the effect of the buffer blasting reduces the possibility of crest area highwall subsidence. In order to prevent far field subsidence damage, it is necessary to compile subsidence plans which (Butcher et al. 2001) denote areas where the safety factors of underground workings are below acceptable norms. Once these plans have been compiled and hazard areas identified, buffer lengths can be extended, ramps and haul roads repositioned and no mining zones determined.

Conclusions

Traditionally open cast mining has been conducted under near ideal conditions in South Africa. However, with the exhaustion of virgin coal seams, and the subsequent focus on pillar extraction, geotechnical conditions have deteriorated. Under such conditions higher geotechnical input is required to ensure safe highwall design. This design work should encompass a geotechnical assessment of the mining lease area, the construction of a geotechnical domain model and a standard slope stability analysis. Cognizance must also be taken of the different geotechnical challenges posed by buffer blasted highwalls.

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