Basic principles for stable gullies in the gold and platinum mines of South Africa

by K. Naidoo* and M.F. Handley†

Synopsis

Gullies are the vital in-stope excavations that provide access for mining personnel and material to, and mined ore from, the producing faces in the tabular hard rock mines. They pose a serious problem in most mines because they induce stress orientations, which, combined with blast damage, produce adverse rock fracture patterns that contribute to the loss of hangingwall and sidewall integrity. Rock-related injury statistics confirm this by highlighting gullies as the second-highest risk area in South African hard rock mines. Inappropriate gully geometries, poor blasting practice, and non-adherence to accepted standards worsen the problem.

The aim of this work is, firstly, to provide guidelines to select the correct gully geometry and appropriate support for a particular geotechnical environment and, secondly, to review the practical issues behind gully safety and stability. In order to meet these aims, this paper reviews the available literature on gullies and their history, and reports on an industry-wide survey of practices and opinions. Then it covers observations from underground visits to 107 gullies situated in the respective geotechnical environments of the Basal Reef, Beatrix Reef, Vaal Reef, Carbon Leader Reef, Ventersdorp Contact Reef, Kimberley Reef, Kalkoenkrans Reef, Merensky Reef, and UG2 Reef. Despite the differing geotechnical conditions and gully geometries, common problems are experienced with geological structure, stress, and fracturing. Results from numerical modelling are also presented to help analyse the underground observations and to quantify the merits of the different gully layouts.

It is concluded that there are no new techniques available to improve gully stability, but that significant improvements in safety are attainable by employing the correct gully geometry for the geotechnical environment, good blasting practice, and appropriate support.

Introduction

A gully is an excavation cut in the immediate footwall or hangingwall of the reef for the purpose of enabling the removal of rock from the face or providing access to the face for mining personnel or material[1]. The gully sidewalls and hangingwall often pose a serious stability problem in the gold and platinum mines in South Africa, since records of fatal rock-related injuries show that they are the site of the second-highest rockfall and rockburst hazard to miners after the stope face[2,3]. Gay *et al.*[4] have indicated that most accidents in stopes occur within 10 m of the stope face and in the gullies which provide access to the working area. From a safety point of view, these are the two most important areas on a mine because of the difficulty in providing support close to the face and the relatively high density of personnel in these areas. Some of the published figures for proportions of rock-related fatal injuries in gullies are given in Table I.

Based on figures presented by Roberts and Jager[2], and Jager and Ryder[5], differing proportions of accidents, summarized in Table II, occur in gullies in the respective mining regions. Despite the higher accident rate in the Carletonville Goldfield, there appear to be disproportionately few gully accidents, while nearly all gully fatalities are the result of rockbursts. The low proportion of fatalities being attributed to gullies does not in any way suggest that gullies are relatively safe in the Carletonville Goldfield, but that the apparently contradictory statistics are perhaps the result of reporting norms, or that the high level of seismicity in the Carletonville Goldfield results in the gullies being adequately supported for

Table I

Proportion of industry-wide rock-related fatal injuries in gullies

Period	Rock-related fatal injuries in gullies	Rockburst related	Rockfall related
1990[2]	17%	-	-
1991-1992[4]	14.2%	-	-
1990-1997[5]	14.6%	8.4%	6.2%

Sources of statistics: Roberts and Jager[2], Roberts[4], and Jager and Ryder[5].

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* *Formerly a consultant with Itasca Africa (Pty) Ltd, Booysens, Republic of South Africa.*

† *Associate Professor of Rock Mechanics, Department of Mining Engineering, University of Pretoria, South Africa.*

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Table II

Comparison of gully accidents in different mining districts

Mining district	Total rock-related fatal injuries per million square metres mined	Proportion of rock-related fatal injuries in gullies	Rock-related fatal injuries in gullies per million square metres mined
Orange Free State	9.65	27%	2.61
Klerksdorp	14.65	23%	3.37
Carletonville	22.15	5%	1.11

Figures compiled from Roberts and Jager[2], and Jager and Ryder[5].

rockfalls, but still inadequately supported in the case of rockbursts. The Carletonville Goldfield statistics in Table II contradict perceived proportions of accidents in gullies, since gullies in the Carletonville Goldfield are often severely affected by rockbursts, especially in backfilled stopes. Three out of five gully fatalities in the Carletonville Goldfield occur either in a winch chamber or at the intersection of strike and dip gullies, where spans are greatest[2]. In contrast to the Carletonville Goldfield, 89% of gully fatalities in the Orange Free State and Klerksdorp Goldfields were due to rockfalls, of which 50% occurred at dip and strike gully intersections, where spans are greatest[2].

In shallow mines, geological discontinuities are the main cause of falls of ground in gullies because there is little or no horizontal compressive stress in the stope hangingwall to clamp discontinuity-bounded blocks of rock together. Studies of the geometry of falls in gold mines show that most falls cover 2 m^2 to 5 m^2 and the initial fall is that of an acute triangular prism[6] bounded by discontinuities dipping between 25° and 70°[6]. In the intermediate depth to deep mines, the area extending about 6 m up dip from the strike gully between the face and the first row of support is particularly vulnerable to falls of ground. This area usually has a low support density because of face scraping, and there is always a complex pattern of mining-induced fracturing caused by the intersection of the face and the up dip gully siding, which promotes hangingwall instability. Bedding plays a major role in falls of ground at all depths, especially if partings with poor cohesion separate the strata.

Correct cutting of strike gully sidings is often neglected in all the goldfields, mainly because gully sidings are allowed to lag, and then drilled down dip and blasted to create the siding over several metres. Rock-bolting in gullies has been shown to reduce falls of ground in the Orange Free State, while grouted rebar support was seen as an effective rockfall support but an ineffective rockburst support in the gullies of the Klerksdorp Goldfield[2].

Based on a study of underground rock-related accident statistics in hard-rock mines, Spearing[7] reported the following as the most hazardous areas in gullies:

- The intersection between the gully and the stope face
- Boxhole intersections with gullies
- Winch beds adjacent to the gully.

These are a few examples of gully problems that may arise, and solutions have been derived in practice to cope with most conditions. There is reluctance on the part of mine personnel to implement optimal gully procedures because they are onerous, and the problems are often intermittent in nature.

Corrective procedures often involve considerable additional effort and, if not carried out properly, can make situations worse. For example, cutting a siding on the down dip side of a gully generally involves time-consuming hand cleaning. As a result, down dip sidings are often cut just deep enough to build a pack. If a seismic event occurs down dip of the gully there is no space for broken rock to move, and the packs are forcibly ejected into the gully, sometimes with fatal consequences. This practice is very difficult to correct underground because it means cutting the siding deeper in the limited space behind a row of installed packs.

This paper comprises two main sections. First, we review current gully practices on the gold and platinum mines, based on published information and data gathered from underground visits to gold and platinum mining operations. Second, we evaluate the factors that influence gully hazards and design aspects that can alleviate or reduce these hazards. Finally, we propose a set of simple guidelines for best gully practice.

Review of industry practices and opinions

Industry practices are reviewed by two approaches, firstly from published literature, and then from information based on the opinions of practitioners on the mines. What follows is a summary of work reported by Naidoo[8] and Leach *et al.*[9].

Literature Survey

Since mining commenced in the Witwatersrand Basin and the Bushveld Complex, a large body of information on mining practices has been published, by far the largest proportion coming from the gold mines. The literature on stope gullies, spanning some seventy years, falls into two categories. The first comprises technical guidelines written by technical services staff or researchers. The second are non-technical in nature, often providing good examples of mine standards that have been implemented underground. In some cases, these show divergence from the technical guidelines in order to accommodate mining practice. It is clear that many of the primary causes of gully problems have probably been recognized for over 70 years. It is also clear that corrective action is largely unpopular, as it makes practical mining operations more complex. Most documented cases show that while mines recognize the need and are prepared to use sidings in areas of higher stress or rockburst hazard, the gully is invariably advanced as a heading with sidings cut some distance behind the advancing face.

The term 'gully' had not yet been adopted when Watermeyer and Hoffenberg wrote their book on Witwatersrand mining practice in 1932[10]. At that time, there were no gullies but on-reef drives, serving as both stope accesses, exploration drives, and tramming routes for removal of broken rock. As mining advanced to greater depths, there was a shift from on-reef drives carrying track-bound hoppers to scraper and boxhole layouts, with haulages sited in the footwall. Scrapers were a necessary addition for the development of the stope gully, and were first introduced on the Modderfontein 'B' Gold Mine in 1924[11] but were still used infrequently in stopes in the 1940s[12]. For a time these excavations were referred to as strike slusher drifts (SSDs), before 'strike gully' became the generally applied term. A considerable volume of published literature pertaining to gully design methods originated at this time[13,14]. The term 'gully' then became applied to a dedicated cleaning route, cut as part of the stoping operation. Gullies were originally cut into the footwall, but some mines e.g. East Rand Proprietary Mines, Blyvooruitzicht, and Durban Roodepoort Deep, cut gullies in the hangingwall in some areas.

By the 1960s, a change had generally taken place in the way in which tabular reefs were mined, and stope gullies with scrapers were in use across the industry. This access layout is less prone to stress and rockburst damage, while scrapers in smaller on-reef excavations improved mining efficiency. During the 1980s, some mines introduced trackless Load-haul-dump (LHD) cleaning equipment, permitting greater flexibility in mining operations, but creating a wider in-stope gully (or roadway) excavation, accompanied by instability and, ultimately, higher operating costs.

Renewed technical assessment of gully geometry and support came after 1960. In particular the necessity of adopting excavation shapes that manipulate, or optimize, stress fracture patterns to assist support was recognized[15] and became well defined in the middle to late 1970s[14,16]. From about 1970, introducing a siding or a ledge to move stress damage away from the gully became a universally adopted recommendation. An example of the variation in stope gully geometries in use at the time is shown in Figure 1. In the mid-1970s, research was based on trying to alleviate and optimize stress fracture patterns as mining progressed to depths of 3000 metres or more. Later research focused on support in mines, and innovations such as gully-support packs with tailored yieldability and stiffness characteristics were introduced[4].

Despite the many years of research and discussion, very few guidelines have ever been published for gully practices, although several recent publications address areas such as design methodology for stable gully support, good blasting practice, minimizing gully spans, preconditioning and other techniques to improve gully stability, especially in rockburst-prone mines[16,17,18]. Although the literature is extensive and informative, it fails to show when the gully geometry should change, or which gully geometries are best to accommodate changes in geotechnical conditions.

Industry opinion survey

The literature broadly indicates a range of best gully practices. Taking these as a base, it was considered essential to examine current industry practices as a means of gauging successful and poor operational methods, together with the existing level of compliance to best gully practice. Respondents at the gold and platinum mines were asked to fill in a questionnaire addressing the following issues:

- What do you perceive as a siding?
- What is the role/purpose of a siding?
- What is your opinion on stable gully spans?
- What is your opinion on effective gully support?
- What is your opinion of gully stability in seismic versus non-seismic areas?
- What are the definitions of best practice for gully geometry?
- How would you minimize fall of ground hazards in gullies?

In general, it was found that industry opinions on gully design and support requirements are often contradictory. In particular, there are differing opinions between rock engineers and mining personnel.

When mining with an underhand layout, respondents almost unanimously prefer a narrow advance strike gully (ASG) without a down dip siding if possible. A siding would

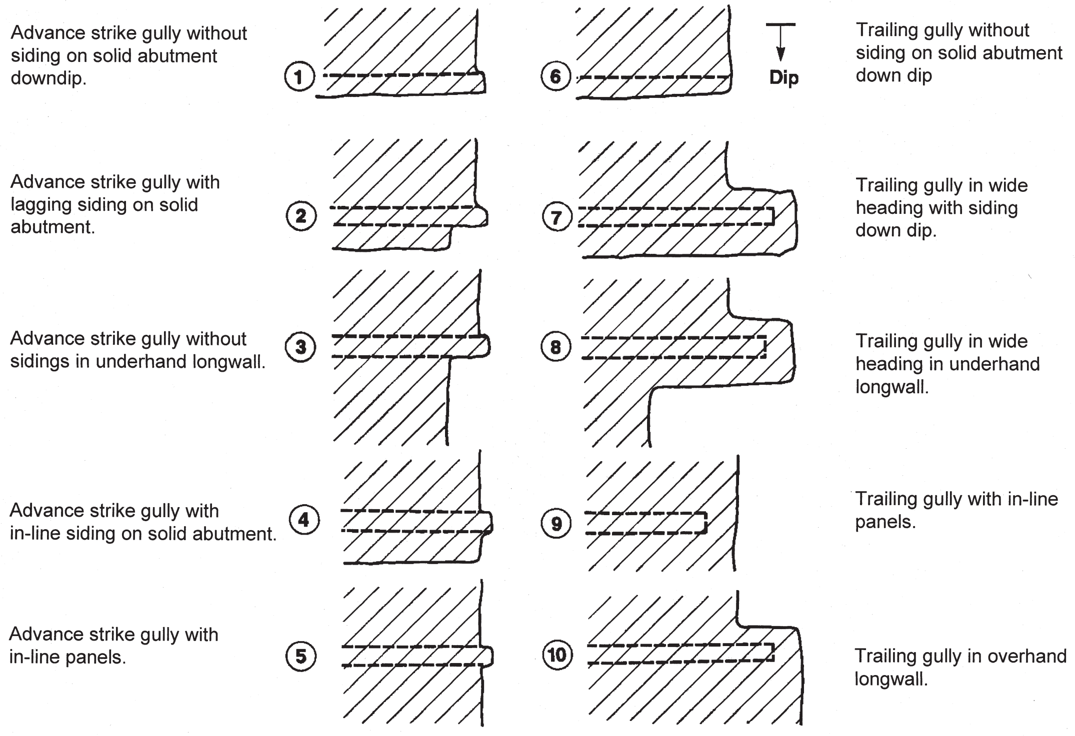


Figure 1—Examples of gully geometries in use (after Chamber of Mines Research Organization[16])

be carried on the down dip side of the gully some distance back from the face only if it is necessary. There are two practical mining advantages to this approach:

- The ASG provides a free breaking point for the stope blast at the panel toe
- The ASG and siding can be blasted independently of the stope panel.

Sidings are considered a necessary nuisance because they have to be cleaned by hand. Wide headings are only well accepted on the deeper mines where other layouts have been proven to result in intolerable conditions. Overhand mining layouts, where only one gully at the bottom of the raise line or longwall needs to be advanced and the other gullies are footwall lifted within panels, are favoured for deep mining conditions. Gully conditions in these layouts are generally acceptable and from the mining point of view, there is some flexibility in terms of gully advance because it only needs to be a small distance ahead of the lagging face.

Sidings on gold mines are perceived to be an on-reef cut with dimension generally not less than 1 to 2 metres. In general, it is accepted that the width of the cut should be such that the abutment stress is removed to a safe distance from the gully. On shallow platinum mines (less than 400 m deep), a siding is any excavation over and above the dimensions of the gully. This may include a 'shaped' excavation to remove the ground that would become loose due to stress-induced fracturing. This includes the 0.5 m on-reef cut (or small siding) to move a pillar slightly away from the gully to improve gully stability.

Most respondents are undecided on an optimum siding width, and while accepting that the wider the better, wish to keep it to an absolute minimum due to cleaning difficulties when mining down dip of the gully. To ease this cleaning problem, some respondents are prepared to tolerate an off reef siding that is cut horizontally from the gully. The industry recognizes that this can be detrimental to hangingwall stability, particularly when mining reefs such as the Carbon Leader, where a flat siding may intersect the Green Bar, a chloritoid shale that lies about 1–2 m above the reef.

The role of sidings in both gold and platinum mines are generally accepted to be the following:

- To move any stress fracture zone away from the edge of the gully
- To maintain the width-to-height ratio of the pillar in the case of shallow mining layouts using crush pillars
- To be able to install support on both sides of the gully
- To reduce the height of the fracture zone which tends to curve over the gully
- To prevent shearing of the gully hangingwall adjacent to the abutment (including along the edge of a crush pillar).

Favoured gully dimensions are 1.6 m wide by 1.8 m deep in the deeper mines. Shallower mines opt for 2.0 m width. In both cases, an extra 20 cm or so is considered tolerable for the distance between supports across gullies. Many respondents accept that it is impossible to maintain gullies within the standard dimensions for the entire gully life. Time-dependent deterioration would ensure that widths increase and final gully dimensions would be larger than the standards.

The respondents agree that stable gully spans depend on depth, geology, mining geometry, and ground conditions. It is also different for different reefs and regions. Most replied that limiting stable spans are of the order of 2.5 to 3 metres, even at shallow depth. It is generally recognized that whatever gully size is created at the face, it will deteriorate, resulting in an increase in gully width back from the face.

Respondents recognize that unstable conditions will arise where:

- Support is snagged by the scraper and falls out
- Gully walls collapse and support is lost
- Seismicity ejects packs from sidings
- Spans are relatively large, i.e. at tipping points, winch cubbies, or water jet cubbies.

All respondents agree that either additional support needs to be planned (e.g. at cubbies) or remedial work is required in the above cases.

Respondents recognize that gullies must be straight; otherwise sidewall erosion by the gully scraper leads to support collapse. Remedial action is costly and time-consuming because it means re-installing packs on the gully shoulders as well as additional hangingwall support. Other side effects of turning gullies include accumulation of broken rock on the outside circumference of the bend, water accumulation, rope and scraper wear, and changed development layouts (e.g. boxholes) to accommodate the new gully position.

To ensure gullies remain straight, provision of timeous and correct gully direction lines remains the key issue. Pegs tend to get lost through minor falls of ground and then miners take lines ineffectively. Clear marking of gully and pack lines using fluorescent paint is advisable. The responsibility for lines must remain with the team leader and miner. In many mines, only a gully centreline is painted on the hangingwall.

Leads and lags between stope panels are a source for concern wherever stress levels are high enough to initiate stress fracturing. As gullies tend to run adjacent to any long leads which form (either up or down dip), long leads are recognized as being detrimental to gully conditions. In the very deep mines where these conditions are most severe, excessive lead/lags are considered to be anything in excess of 10 to 20 m.

In overhand panel layouts where gullies act as cleaning ways for the panel above and an escape way for the panel below, there is a tendency to only lift the gully just past the face of the lagging panel. Most respondents recognize that this gully should be kept to within 5 m of the leading face, to perform the function of top access to the panel (top gully) and an escape way. It is admitted that the five-metre criterion is met in only ten per cent of the cases, with most top gullies lagging seven to eight metres behind the leading face. On most mines, the upper panel is responsible for this gully, not the lower panel, whose escape gully it is. Possibly this responsibility should change to improve access and safety.

An optimal lead/lag on panels is thought of as 10 m with gullies 2 m ahead of panel faces for cleaning. Poor conditions tend to arise at the panel face/gully intersection where high stress conditions exist. This area is recognized as being particularly hazardous and must be supported. Long leads of 20 m or more aggravate this condition and can contribute to severe hangingwall deterioration in the face-gully area.

Gullies may have to be kept open for long periods, while gully deterioration starts right away. It becomes noticeable 20 m from the face. In some cases, mines have to keep gullies operational for distances up to 150 metres, which means that the greater part of the gully is in a poor state. In addition to this, scrapers do considerable damage to support and the gully sidewalls over time. In these cases, a support-monitoring programme is required, with replacement of support as required. In general, respondents feel that systems of accountability are essential if good gully conditions are to be maintained for long periods.

Platinum respondents view pillars as the most effective gully support, when ground conditions are poor or in a low stress environment. Rigid mine poles supplement the pillars, forming a rigid support system. Additional pillars are left along gullies, and sidings are omitted when highly jointed or faulted ground is encountered. Respondents from the platinum mines all agree that seismicity is not a problem, whereas gold mining respondents cite seismicity to be of prime concern in intermediate and deep mines.

All respondents are concerned by the multiplicity of standards for both gully layout and support and many production personnel express a need for simplification of standards. There is considerable dispute and difference of opinion on gully shoulder support, even amongst respondents from the same mine. Most mining personnel on the deeper mines prefer packs, although there is also enthusiasm for backfill and yielding timber props right up to the gully edges. The use of props on gully sidewalls reduces effort in terms of material transport and installation, and provides a more competent support in deep mining conditions. Sidings remain difficult to support with anything other than packs at all depths, and opinions vary over the need for pre-stressed packs on the gully shoulders.

Hangingwall support in gullies is unpopular and mining personnel would rather avoid it if possible. Most respondents have much confidence in rehabilitation techniques such as ground consolidation and sets with void filling. Basic support rules vary for fault and dyke intersections, but packs are universally considered to be the best support element because of their strength, yieldability and area coverage.

Many respondents agree that smooth-wall blasting should be practiced to reduce the amount of gully sidewall and hangingwall damage. The result is better control of the final gully dimensions and hence the span between supports on opposite sides of the gully. Footwall ripping to advance a gully behind a breast panel face is generally recognized as bad practice.

In summary, there appears to be good agreement between respondents on sidings and their purpose. There is reasonably good agreement on gully shape, gully dimensions, and blasting practice. The decision to use sidings or not elicits widely divergent views. This may reflect a 'gray zone' between shallow depths where no sidings are required, and greater depths, where they become necessary. Despite the consistent opinion on gullies and their geometries, the underground observations reveal that mine standards are not always implemented.

Table III

Summary of underground visits

	No. mines visited	No. gullies visited
Platinum mines	4	43
Gold mines	16	64
Totals	20	107

Underground observations

A series of underground trips were made to 107 gullies industry-wide to obtain a clear picture of gully practices and problems. Table III provides overall statistics of the visits, while Table IV provides details of the geotechnical areas covered by the visits.

All the gully geometries currently in use in the gold and platinum mines can be briefly summarized as follows (see Figure 2 for illustrations).

1. Advance Strike Gully (ASG) cut ahead of faces with pillars left on the down dip side of the gully.
2. ASG cut ahead of faces with pillars left a short distance down dip from the gully shoulder.
3. ASG ahead of the stope panel without down dip siding.
4. ASG with lagging down dip siding.
5. Gully, stope face, and down dip siding in line.
6. Footwall lifted gully inside a wide heading carried ahead of the stope panel face (either the No. 1 gully in overhand longwall, or all gullies in underhand longwall), or footwall lifted gully behind the face in the up-dip corner of each stope panel when employing an overhand stoping layout.

Table IV

Geotechnical details of gullies visited

Reef type	No. of gullies visited	Depths																				
		PLATINUM REEFS																				
Merensky Reef	39	590	600	650	660		880					1800		2000								
UG2 Reef	4					670																
		GOLD REEFS																				
Beatrix Reef	4							900														
Basal Reef	5										1656						2500		2800			
Carbon Leader Reef	20													2000	2100			2701				

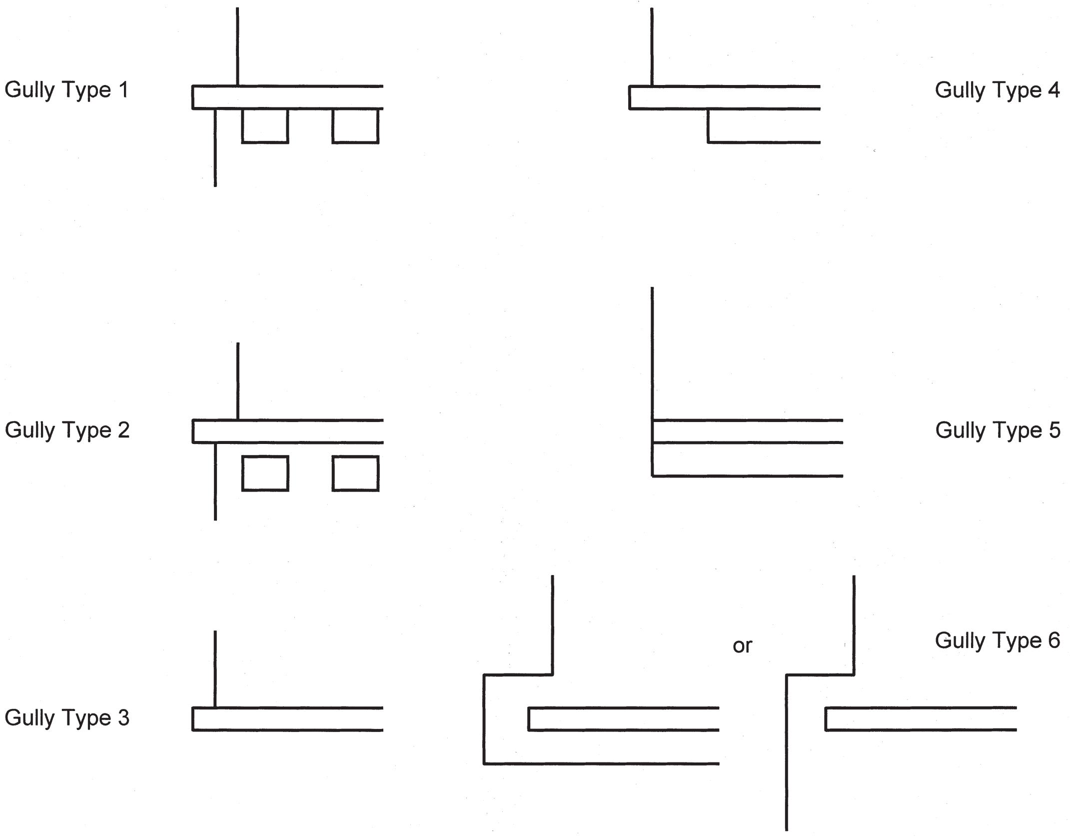


Figure 2—Most common gully geometries in the gold and platinum mines

The numbers in the discussion that follows will refer to the six gully types named above. The literature survey indicates that gullies without sidings are appropriate at shallow depth, ASG types and lagging sidings are tolerable at intermediate depth, while at greater depth where higher stress levels prevail, footwall lifting either in overhand panel configurations or wide headings for the No. 1 gully in overhand longwalls, and in underhand longwall configurations should be practiced. The arrangement of the gully classification broadly reflects this; hence, gully types 1 and 2 tend to be used in shallow mines, types 3 and 4 in intermediate depth mines, while types 5 and 6 are found in deep mines.

The choice of gully standard on each mine is a factor of the overall mining layout, the ore carrying capacity of the gully (related to the panel length it serves), and geotechnical conditions. Local preferences and the severity of problems with one layout or another may also influence choice of gully geometry.

Gully conditions were rated in all the underground visits according to the following simple overall descriptions:

- *Good:* stable conditions, no visible hazards, little or no adverse fracturing, no falls of gully roof
- *Moderate:* some adverse fracturing present, with a potential fall of ground hazard, but appropriate measures have been taken to control the ground
- *Poor:* adverse fractures, evidence of falls of ground, gully sidewall integrity has been lost.

Figures 3 to 5 show scatter plots of depth versus gully type, with condition descriptions according to the above classification shown by the different symbols. There is a clear transition from one gully type to the next with depth, especially evident in Figure 5, which presents gully statistics for the combined gold and platinum industry. However, there are no clear guidelines on which gully geometry to use in which geotechnical conditions. The statistics as plotted indicate that each mine has evolved its own standards over time, and that there is a crude linear relationship between gully type and depth of application.

Despite the loose relationship between gully type and depth of application, there does not seem to be a consistent relationship between gully condition and depth for a specific gully type in Figures 3 to 5. Other variables are clearly also important in influencing gully condition, namely stress regime, geotechnical conditions, mining practice, and support practice. The plotted statistics can therefore only provide the most general guide on which gully geometry to use. Hence, a well-managed gully created by good mining practice may be

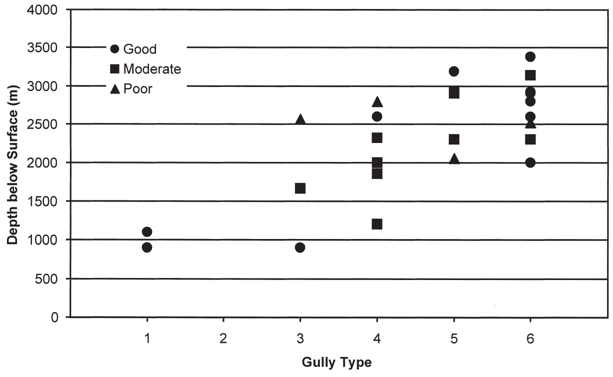


Figure 3—Plot of depth versus gully type for the gold mines

in good condition at depth, even though the geometry chosen is better suited to shallow mining. The converse may also be true — poor gully conditions in a gully geometry suited for depth in a shallow mine.

To illustrate the influence of mining practice, the measured gully width underground has been normalized with the mine standard as a measure of compliance. A value greater than unity thus means that the actual gully width is greater than the mine standard. The data are plotted versus depth in Figures 6, 7 and 8 for the gold, platinum, and combined industries respectively. The symbols used separate good conditions overall (circle) from the gullies with moderate to poor conditions (triangle), to give an indication of how effective it is to keep gullies to within the mine standard.

It appears that using gully span as a measure of compliance might be more appropriate for the platinum mines, because the vertical line at unity separates gullies with good conditions from those with moderate to bad conditions more efficiently in Figure 7 (platinum mines) than it does in Figure 6 (gold mines). Many factors could affect this division, for example blasting practice, age of gully, appropriateness of the mine standard given the geotechnical conditions, and so on. This is true for all depths, as shown in Figures 6, 7, and 8.

Platinum mine gully widths show greater divergence from mine standards than is seen in the gold mines, probably because they are generally shallower, and conditions allow wider gully spans than is generally the case for the deeper gold mines. Gully support methods may also have an influence. The gold mines almost invariably use packs with controlled yielding to support gullies, while the platinum mines use pillars and non-yielding mine poles in most cases.

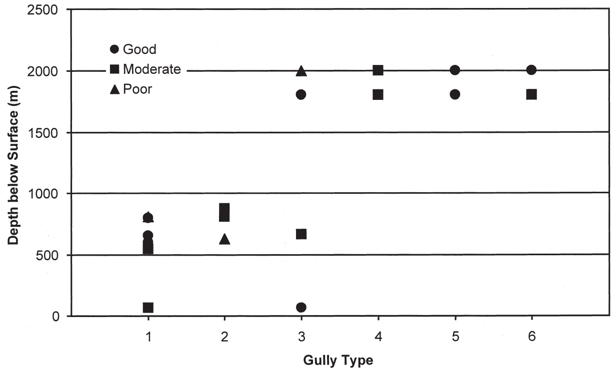


Figure 4—Plot of depth versus gully type for the platinum mines

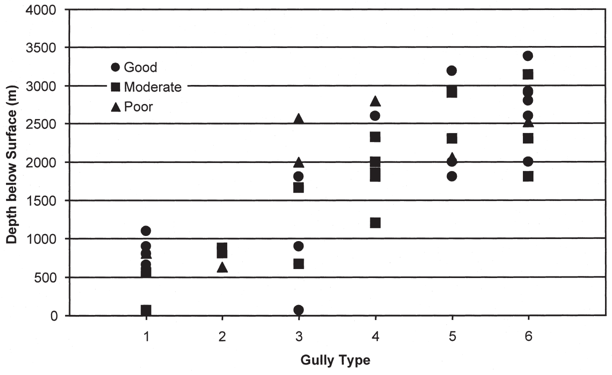


Figure 5—Plot of depth versus gully type for the gold and platinum mines

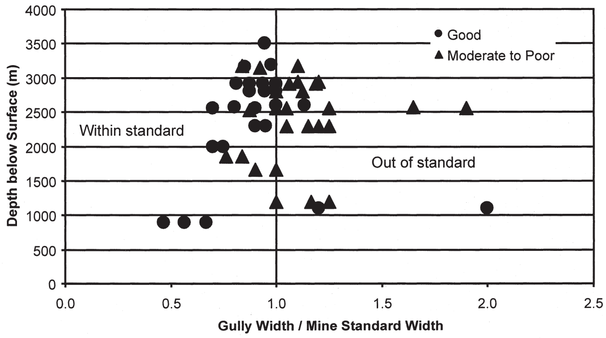


Figure 6—Scatter plot of depth versus gully span divided by mine standard gully span for the gold mines

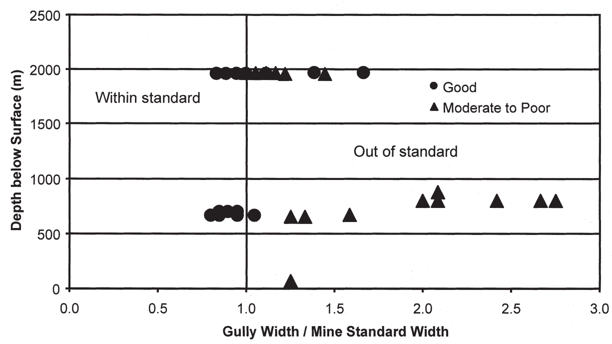


Figure 7—Scatter plot of depth versus gully span divided by mine standard gully span for the platinum mines

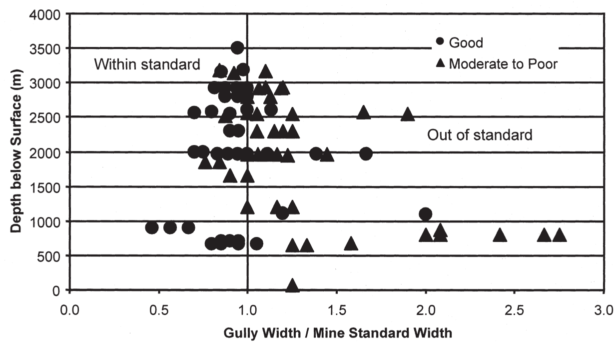


Figure 8—Scatter plot of depth versus gully span divided by mine standard gully span for the gold and platinum mines

The underground observations are not sensitive enough to reveal the true causes of gully instability, since the condition of the rockmass, the geometry of the gully, support type and density, and the stress the gully is subjected to strongly influence stability. These factors can only be objectively addressed by numerical modelling, which will provide quantitative results.

Quantitive evaluation of observations

The previous sections examined industry-wide thinking and practice with regard to gully layout and design in the gold and platinum mines. Underground observations and industry opinion are limited in describing the problem because they are qualitative. The geotechnical conditions that exist around two different gullies can never be identical, making a quantification of the relative merits of different layouts impossible by qualitative means alone. Geotechnical conditions can be incorporated in a numerical model, where it is possible to analyse the relative merits of different gully layouts.

Both two-dimensional and three-dimensional models were developed for analysis by FLAC and FLAC3D respectively[19,20]. The computer programs can be used to simulate the behaviour of structures built in any solid material such as soil or rock, which can undergo inelastic deformation when stresses reach the yield limit of the material. FLAC3D extends the two-dimensional analytical capability of FLAC into three dimensions for cases where a two-dimensional model is inadequate or oversimplified. In many cases this is true for gullies, hence three-dimensional models are considered essential.

Two groups of two-dimensional models were set up, broadly representing a typical Merensky Reef rock mass for the platinum mines, and a strong VCR rock mass for the gold mines. This approach was adopted because underground observations indicate that there are differences in overall rock mass strength between gold and platinum mines that result in the onset of stress fracturing at very different depths. Despite this, the main objective remains to compare the effects of varying geometries, not to establish exactly calibrated back-analyses.

The three-dimensional models assume a generalized quartzitic rock mass without bedding and jointing. The base criteria for the two and three-dimensional models are listed in Table V. These models and their outputs are complex, and deserve a fuller treatment than can be given here. Consequently, Leach[21] is currently preparing a second independent paper detailing the models and the modelling process.

In summary, the objectives of the 2- and 3-dimensional models include:

- To back analyse mechanisms which are observed to lead to gully damage and deterioration.
- To compare the changes in rock mass conditions that are likely to occur when different gully layouts are used, or when gully dimensions such as siding width are varied.
- A quantification of the relative merits of siding versus non-siding gully geometries under identical geotechnical conditions based on rock damage and deformation around the gully. Cases for shallow mining, where pillars are left adjacent to gullies, and deeper mining operations are considered (two-dimensional modelling).
- The effect of varying rock mass strength and geological stratigraphy on gully behaviour (two-dimensional modelling).
- The effect of increasing dip on damage patterns around gullies (two-dimensional modelling).
- The effect of varying dimensions for heading width and lead, siding width and lag, and position of footwall lifting of gullies. Each of these parameters has limiting values if orientation of stress fracturing is to be successfully manipulated to optimize gully stability (two- and three-dimensional modelling).

Table V

Basic criteria used in numerical models

	FLAC models (two dimensional)		FLAC3D models
Depth	1800 m	2500 m	2000 m and 3000 m
Rock mass	Pyroxenite	Lava – hangingwall Quartzite – f/wall	Quartzite
Reef dip	20 degrees	20 degrees and 40 degrees	20 degrees
Vertical stress	49 MPa	68 MPa	54 and 81 MPa
k-ratio	0.5, 1 and 2	0.5	0.5
Horizontal stress	25 MPa	34 MPa	27 and 40 MPa

The broad conclusions from the modelling are listed in two parts below. For shallow mines, it is concluded that:

1. In mining layouts where pillars are used, a siding is desirable if any form of stress fracturing develops in the pillars;
2. The minimum siding width between gully and pillar is 2 m, or the 45 degree rule can be applied to determining the minimum on-reef siding width between the gully and the pillar if it needs to be more than 2 m (see Figure 9 for details);
3. Sidings smaller than 2 m are ineffective, both as a means of improving pillar performance, and as a way of decreasing gully sidewall damage;
4. Hangingwall stability is generally good;
5. There is a tendency for increased hangingwall and sidewall damage if the gully is cut as a heading in front of the stope panel;
6. If an ASG with a lagging siding is used, the siding should be cut within 6 m of the ASG heading face;
7. Gully damage can be directly attributed to the level of stress applied to it during its history.

For intermediate and deep mines, it is concluded that:

1. There appears to be between 30% and 50% more stress damage to the rockmass when omitting sidings, compared with including a siding;
2. In addition to the extra damage, the induced fracture orientations are more difficult to support;
3. When stresses are high enough to induce fracturing, any method where a siding is omitted or permitted to lag on the down dip side of the gully is not desirable;
4. Increase in reef dip tends to increase stresses in gully sidewalls, and may require an increase in siding width (see conclusion 6 below);
5. Gullies without sidings become more highly loaded than those with sidings;
6. Siding widths for all gullies should be determined using a simple 45 degree rule based on gully depth and reef dip (see Figure 9, and note that it may be convenient to cut a hangingwall gully in some cases);
7. The two-dimensional models indicate that it is best to excavate the stope face, the gully, and siding simultaneously in an in-line configuration in underhand longwalls;
8. A wide heading with a footwall lifted gully at the bottom of each panel is second choice for underhand longwalls;

9. The three-dimensional models confirm that lagging sidings and no sidings are not desirable at depth;
10. A wide heading with a footwall lifted gully is the best option for the No. 1 gully in an overhand longwall, because rockmass damage around the gully is minimized under these conditions;
11. The in-line configuration described in point 7 above is the next best choice for overhand longwalls at depth;
12. Wide headings with leads of up to 10 m do not appear to result in any obviously detrimental effects;
13. No obvious limitations to heading width arise from the modelling, excepting that headings less than 6 m wide are liable to allow damage to lifted gully sidewalls within the heading;
14. Gully damage can be directly attributed to the level of stress applied to it during its history.

On balance, it can be concluded that gully sidings may be omitted in shallow mines in good conditions, and in situations where the gully will not be loaded by additional stresses during its useful life. Omission of sidings or allowing lagging sidings in intermediate to deep mines should be avoided, and that either wide headings for overhand longwalls or the in-line configuration for underhand longwalls are the best options. The modelling also confirms that the 45-degree rule (as used for siting off reef development in a deep mining environment) is appropriate for choosing the optimal gully position relative to a pillar or an abutment.

Guidelines for gully geometries

Due to differences in rock mass strength and the overall *in situ* stress regime, stress fracture damage is observed at shallower depths in the platinum mines than in the gold mines. Thus depth is not a good descriptor for classifying the use of different gully types in the gold and platinum mines. It is better to use a stress criterion instead, which defines three classifications for the gold and platinum mines. The stress criterion is called the *maximum principal stress criterion*, and is applied as follows:

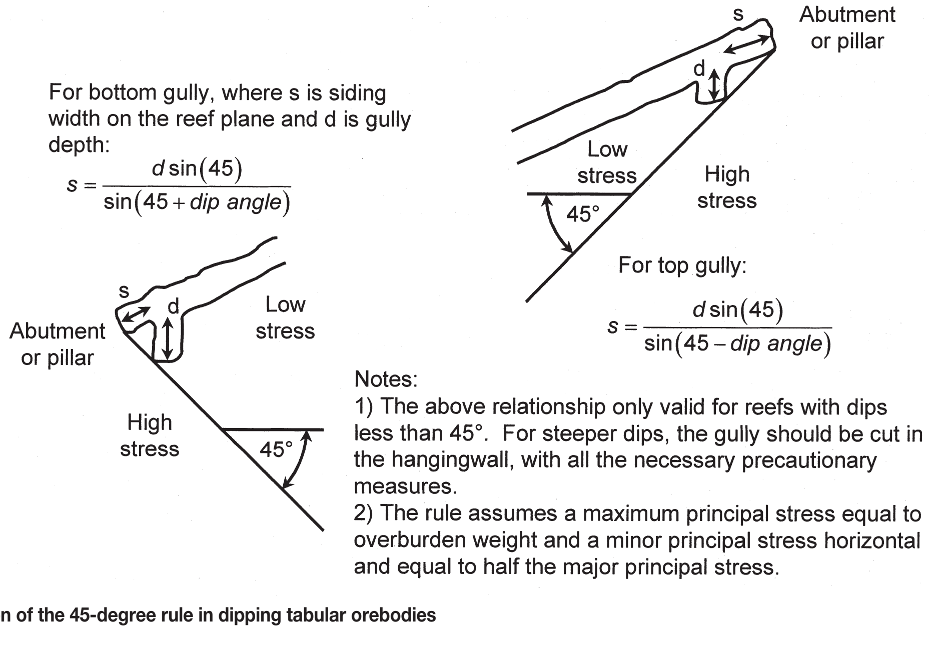
- *Low stress:* $s_1 < 0.15s_c$, *where* s_c *is the UCS of intact rock* — instability is controlled by geological structure and stress damage is generally not apparent.
- *Moderate stress:* ($0.15s_c \leq s_1 < 0.30s_c$) — selected methods must cope with instability resulting from stress fracture interaction with geological structure such as bedding, jointing, and weak strata.
- *High stress:* ($s_1 \geq 0.30s_c$) — conditions where stress-induced fractures are the dominant and most densely spaced discontinuities, in many instances making geological structure inconsequential. Seismicity is often a concern.

A chart is presented in Table VI, for gold and platinum mines. The Table shows that the *maximum principal stress criterion* has divisions at different depths in the gold and platinum mines because of the differing geotechnical conditions between the two groups of mines.

The exact limits of the stress class intervals are not fixed and may change from one situation to another. Thus, practitioners are advised to use the Table only as a guide, and to optimize their designs with numerical modelling that takes into account the unique circumstances on the mine. The observations made in this study have been unable to identify a preferred gully support system; therefore, the current systems in use are still applicable, if they are able to cope with closure in the case of the intermediate and high stress situations. More details of support and basic support practice are available in Naidoo[8], Leach *et al.*[9], and Leach *et al.*[22].

Conclusions

No new techniques are available to effect substantial improvements in gully safety. The correct geometry and design of appropriate dimensions such as the gully siding width and gully depth will go a long way to ensuring stability. Proper design, coupled with good blasting practice and appropriate support measures (including minimized gully span and span between supports across the gully), should bring about substantial improvements in gully safety. Some of the measures, such as the down dip siding width,

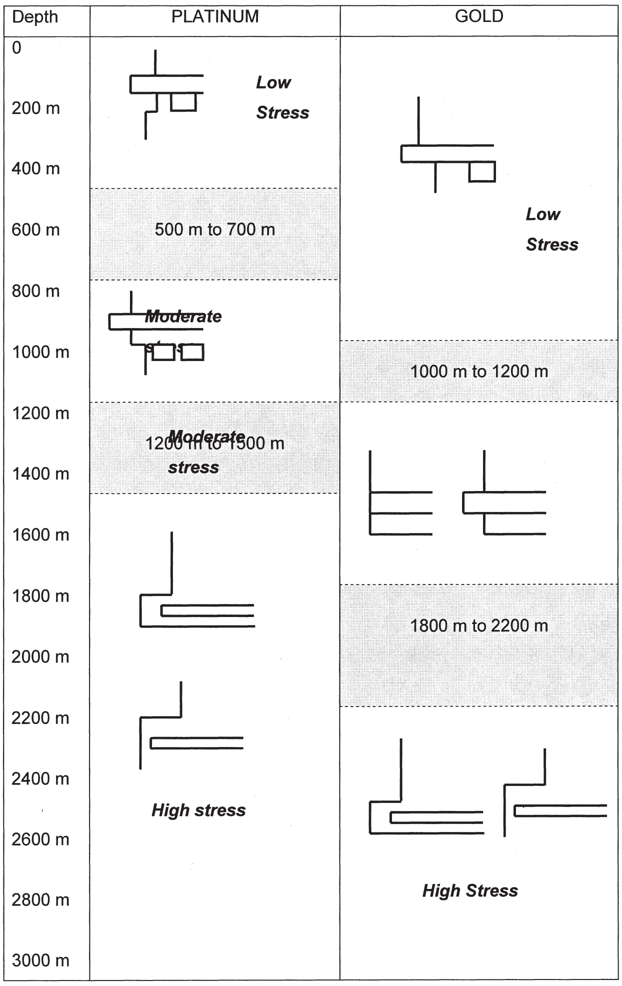


Notes:
1) The above relationship only valid for reefs with dips less than 45°. For steeper dips, the gully should be cut in the hangingwall, with all the necessary precautionary measures.
2) The rule assumes a maximum principal stress equal to overburden weight and a minor principal stress horizontal and equal to half the major principal stress.

Figure 9—The application of the 45-degree rule in dipping tabular orebodies

Table VI

Basic gully geometry guide



are difficult to implement and it is suggested that ways to make this easier and more practicable underground should be researched.

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