Factors influencing the severity of rockburst damage in South African gold mines

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Synopsis

Detailed investigations have been conducted into 21 rockbursts which caused damage to excavations in deep South African gold mines, in many instances resulting in the death or serious injury of workers. The objective of this study is to determine the principal factors controlling the severity and distribution of damage, so that strategies to reduce the hazard of rockbursts may be developed. It was found that the source mechanism is often controlled by the mine layout, and regional structures such as faults and dykes; while local rock conditions and support systems strongly influence the location and severity of damage. In the short term the most important lever for reducing the rockburst hazard is the effective implementation of existing rock engineering knowledge and technology.

Introduction

The severity of rockburst damage often varies greatly. One panel in a longwall may be severely damaged, while an adjacent panel (perhaps even closer to the focus of the seismic event) is unscathed. The condition of a tunnel may change from being sound to one of total collapse over a distance of a few metres. Why is this so? A research project was initiated in 1994 with the objective of determining the factors that control the distribution and severity of rockburst damage. It is believed that a detailed understanding of both the source and damage mechanisms, and the application of this knowledge to the design and support of excavations, will lead to a reduction in the hazard posed by rockbursts.

Twenty-one investigations were conducted in the period from 1994 to mid-1997. The majority of investigations took place in the Far West Rand goldfield, with several investigations in the Klerksdorp, West Rand and East Rand goldfields. Descriptions of several of these investigations have been published (Durrheim *et al*[1,2,3]). In this article we synthesize the findings of these investigations with the aim of highlighting common themes and key issues.

Methodology

The following procedure is generally adopted in the investigation of a rockburst.

- The team of specialists visits the site shortly after the event, in most cases prior to any rehabilitation so that the only disturbance is due to the rescue operation. The damage to the excavation and support elements is carefully studied, dynamic closure is estimated, and mining-induced fractures, joints and other geological features are recorded. Interviews are held with witnesses to the rockburst and rock engineering staff at the mine. Each member of the team has a good general knowledge of rock engineering and mining in addition to an area of specialist expertise (e.g. layouts, support, geology, seismology).
- Seismograms of the incident are used to determine the source parameters.
- The seismic history of the area in the vicinity of the rockburst and nearby structures (dykes and faults) is assessed.
- Numerical modelling is used to evaluate the mining layout and sequence at the time of the rockburst by calculating parameters such as Energy Release Rate and Excess Shear Stress.
- Support elements such as props and tendons may be recovered from the rockburst site and tested in the laboratory.
- Rock samples may be collected so that the properties of the strata can be determined.
- Future mining strategies are investigated and recommendations formulated.

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Layout and mining sequence

Guidelines and empirical design criteria found in publications such as *An Industry Guide to Methods of Ameliorating the Hazards of Rockfalls and Rockbursts* (COMRO[4]) are generally used for the design of excavations. During the course of the rockburst investigations it was found that some of these guidelines and criteria have limitations which are not always appreciated by the rock mechanics practitioner. In some instances, the limitations are not clearly expressed in the publications. The notes that follow for the most part endorse existing guidelines, but in some instances reflect a slowly evolving change in knowledge and approach.

Remnants

The mining of remnants poses particular challenges as these parts of the ore body have usually been left because of geological complications such as faulting, or because of damage caused by a previous rockburst.

The formation of remnants should be avoided in a longwall situation. If possible, underhand mining from the raise should be carried out. The mining of the remnant between approaching longwall faces is inherently hazardous and must be carefully managed. If up-dip mining is being practised, the up-dip faces should be changed to a breast configuration sufficiently far away to prevent the development of a heading in a very high stress environment.

The formation of rectangular or L-shaped remnants should be avoided, as the whole structure may fail in a single event. Rather, a triangular remnant should be formed and mined in a direction such that the part to be mined last is closest to the nearest large solid area, allowing the apex of the triangle to crush progressively.

Pillar width : height ratios

If trenching is carried out owing to a sudden change in reef elevation (e.g. faulting or 'roll'), the effective unconfined height of the remnant or pillar is increased (Figure 1). Calculations of the pillar dimension using guidelines based on the width : height ratio should be treated with caution.

Face orientation

The angle between the longwall and geological features such as dykes, faults, or dominant joint sets must be carefully considered. Experience shows that an angle greater than 30° between the feature and the orientation of the longwall (not the individual panel) is desirable.

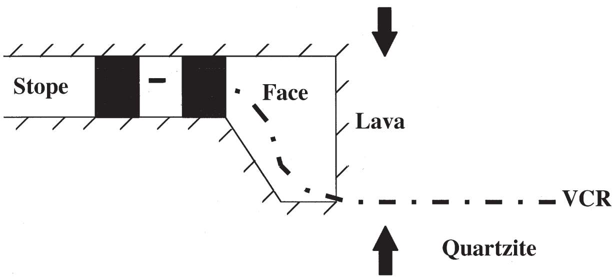

Figure 1—Increased effective unconfined height of remnant or pillar owing to a change in reef elevation

In situ *stress*

The *in situ* stress is an important factor in designing underground excavations, and cannot simply be assumed to be the overburden load yielding a k-ratio of 0,5. Measurements should be made to determine whether any anomalous stress state exists. In some areas significant residual stresses have been found to exist giving k-ratios as high as 1,8.

Shape of stope face

Panel length and lead/lags require trade-offs between practical production constraints and the theoretical ideal. The use of shorter panels is recommended to limit the extent of ruptures along face-parallel shears and the consequent damage, and to facilitate escape from rockburst damaged panels. A long straight face should be avoided. Gully headings in advance of long straight faces are particularly prone to damage.

Panels lagging by large amounts are subjected to high ERR's and should be supported particularly well, with a strictly enforced 'no blast if support not up to standard' regulation. The leading panels should be stopped or slowed down to remedy the situation.

Service excavations and facilities

Facilities such as the stope entrance infrastructure (timber and material bay), refuge bay and waiting place should be located away from seismically hazardous areas such as faults.

Faults

Mining in the vicinity of major faults may result in increased fault instability, and the use of bracket pillars parallel to the major faults should be considered.

Stope access

The number of accessways to the face should be adequate for the rescue and rehabilitation work that may be required following a rockburst.

Multi-reef mining

Relative face positions and the resultant stress fields should be carefully considered. One face should lag the other by an amount equal to the middling distance, until the reef separation is such that face stresses do not interact significantly.

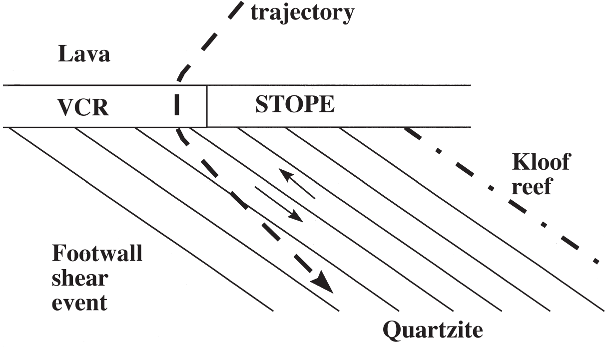

Figure 2—The possibility of shear slip between footwall strata with low cohesion may be increased by an unfavourable stress trajectory

Angular unconformities

If strata are not parallel, the refraction of the stress field due to mining may increase the shear stress on a bedding plane with low cohesion (Figure 2). This may contribute to a seismic event.

Stabilizing pillars and abutments

Highly stressed stabilizing pillars and abutments may experience foundation failure. The situation may be alleviated by higher volumes of backfill and improved placement techniques, thereby reducing the likelihood of further foundation failures. For mines without backfill systems, consideration may need to be given to changes in layout including increasing pillar size and reducing the spacing between pillars.

Numerical modelling

When mining layouts are designed, the guidelines and empirical criteria are often supplemented by the calculation of Energy Release Rate (ERR) and Excess Shear Stress (ESS) using standard numerical modelling computer programs. During the rockburst investigations it was found that the fundamental assumptions of elastic modelling techniques, and the need to apply engineering judgement in the interpretation of the results, is not always appreciated by the rock engineers on the mines.

Mines should develop strategies to mine in the proximity of geological discontinuities such as dykes and faults using back analyses of past rockbursts. ESS and ERR should provide empirical design criteria.

Extreme care must be taken in the interpretation of calculated stresses, ERR and ESS. The ratio of the average pillar stress (APS) to the uniaxial compressive strength (UCS) of the rock comprising the pillar is commonly used as an emprical design criterion. Elastic modelling programs do not take the fracturing of the face into account, and produce unrealistically high values of stress at the edges of pillars and abutments. In reality these areas fracture and crush, shifting the load away from the face. The core of the pillar is subjected to greater stress than is indicated by the numerical model, and the APS produced by the elastic model is not appropriate for calculating the APS/UCS ratio. This can become critical when the pillar dimensions are small.

The mining and seismic history should be considered when assigning strength to blocks of ground. Narrow pillars, small remnants and areas that have hosted large seismic events should not be modelled as solid, but rather as failed areas incapable of bearing significant load. Footwall punching and complete stope closure may have relieved stresses within pillars and remnants.

Other important factors are the sizes of mesh and the window used for numerical modelling. The mesh size should be small enough to represent the local mining geometry in adequate detail, while the window size should be large enough to take into account all significant contributions to the stress in the area of interest.

Tunnels and service excavations

The quality of the support system is of key importance. Long term excavations that are likely to be subjected to seismicity during their lifetimes should be supported with pre-stressed yielding units that can accommodate shear deformations (e.g. grouted rope anchors or cone bolts), integrated with mesh and lacing. In areas where severe shaking is expected, these supports should be supplemented with shotcrete.

The collapse of large sections of tunnel may be precipitated by the failure of a single weak link. Consequently it is important that the lacing be properly clamped so that the failure of a single cable does not cause the whole system to unravel.

Rehabilitation of tunnels and shafts by ‘bleeding-off’ the fractured rock may have unforseen results. For example, the barring of unstable rock from the hangingwall of an incline shaft had the effect of increasing the height-to-width ratio of the pillar separating the shaft from an old stope, causing the previously stable pillar to fail. Furthermore, it is also crucial that adequate temporary support is in place while rehabilitation is being performed.

Other vulnerable situations arise when tunnels traverse faults, approach the reef intersection, or the stress régime changes owing to over- or under-stoping.

Gullies

Gully support

Rockburst-resistant support must be installed in gullies, especially when traversing faults and dykes. The use of softer support on gully edges (e.g. soft packs, or bringing backfill down to the gully edge with gaps left for storage) is encouraged. The integration of elongates with packs on gullies appears to show improved performance when compared to current standards. The idea of using elongates with special headboards to allow lagging across gullies also looks promising.

The gully heading should be supported with rockburst-resistant support (such as rapid-yielding hydraulic props with headboards) installed in the face area.

Gullies adjacent to pillars and abutments

Gullies along pillars and abutments are particularly prone to damage, as these areas can host large seismic events and the gullies are exposed to high stresses over long distances. The support systems in these gullies should be especially robust. Continual recognition must be given to the fact that rockbursts are the destructive or damaging manifestations of the seismic energy release. Innovative thinking is necessary. Some methods of reducing the rockburst hazard are suggested here.

- Use foam cement in the south siding alongside and behind the packs to absorb the impact of the dilating rock and to maintain the integrity of the hangingwall rocks.
- Use yield tendons together with some form of areal support to pin the gully hangingwall. This type of support is more capable of accommodating shear along weak planes parallel to the hangingwall. Angle this support to be at right angles to the dominant fracturing.
- Get backfill closer to the gully edge. Prevent backfill from dilating into the gully by using mesh between packs.

- Precondition the pillar edges by drilling and blasting from the heading. This will create a buffer zone and ensure that the shear zone, resulting from foundation failure, is that much more distant from the pillar edge.
- The gully siding should be deep enough so that the pillar edge and the packs on the down dip side are separated by at least a metre. This will reduce the likelihood of buckling due to violent dilation of rock from the pillar edge. Use foam cement to maintain the integrity of the hangingwall in this area.

Gully sidewalls

Gully packs sometimes collapse or are ejected during rockbursts due to poor foundations. The sidewall may be damaged by scraping, poor blasting practice, or may have failed due to the gully packs bearing excessively high loads.

Gullies in Carbon Leader Reef stopes

Carbon Leader Reef gullies appear to be prone to damage due to the geotechnical properties of the hangingwall strata. The Carbon Leader Reef is immediately overlain by a competent siliceous quartzite, 1,4 m to 4 m in thickness in the Carletonville area; which is in turn overlain by the Green Bar, a 1 m to 2,5 m thick argillaceous unit (Engelbrecht *et al*[5]). Owing to the poor cohesion between the hangingwall quartzite and the Green Bar, the quartzite beam is susceptible to fracture and collapse. In some instances there has apparently been lateral motion along the Green Bar. In one case the gully had been excavated along the lower edge of the stabilizing pillar where a prominent set of mining-induced fractures orientated parallel to the edge of the pillar was present, giving rise to poor hangingwall conditions.

Strike gully sidings must be mined strictly on dip so that the Green Bar contact is kept a maximum distance above the stope. The final cleaning of the siding can take place from the following down-dip panel where applicable.

Stopes

Support

Rockburst resistant support such as rapid-yielding hydraulic props or yielding elongates must be installed in the face area. This is especially critical at the top and bottom of the panels where cross-fracturing exists due to the adjacent leading or lagging panel. Non-yielding support elements such as mechanical props and mine poles have very low energy absorption capabilities under rockburst conditions. Headboards should be fitted to props and elongates to limit falls of ground, especially in areas where the hangingwall is friable and prone to fragmentation. Face area support should be in place 24 hours a day. Back areas should be barricaded to prevent casual access, as these areas are prone to shake out.

Brows

It is imperative that horizontal confinement be applied to brows formed by falls of ground, negotiation of faults and 'rolls'.

'Rolls' in the Ventersdorp Contact Reef

Special care should be taken to support the hangingwall when mining in the vicinity of rolls, especially when associated with bedding-parallel faulting, as the frequency of weak calcite-coated joints appears to increase in these areas. The rock hangingwall has a greater propensity to disintegrate when subjected to seismically induced shaking. An additional hazard is posed by the exposure of lava in the face. The lava has a higher uniaxial compressive strength (UCS) and Young's modulus than the VCR, and can therefore store more strain energy and appears to be prone to face bursting (see Figure 1).

Backfill

It should be ensured that the backfill bags are large enough to tightly fill the stope. In areas where fall out of the hangingwall has occurred, larger backfill bags should be used. Backfill should be extended to the gully packs. This would increase the filling by about 5% and reduce the potential for falls of ground between the gully packs.

Stoping width

Careful blasting should be practised and a conservative blast design implemented, as a reduction in stoping width will improve the effectiveness of both the face area support and the backfill.

Rapid-yielding hydraulic props (RYHPs)

RYHPs were introduced almost 30 years ago, and were received with great acclaim once initial 'teething' problems had been overcome. For more than two decades their performance was deemed satisfactory. In recent years, however, the mining industry has become reluctant to continue using RYHPs owing to operational difficulties. The real cause of the poor performance of RYHPs should be determined. Factors which could contribute to the high fall-out rate follow.

- Failure to use loadspreaders. In highly fractured ground the relatively small diameter of the end of the prop or extensions could 'punch' a few millimetres and thus drop load. A similar effect is obtained from setting on a poorly cleaned footwall.
- Pump pressures are incorrect. This could be caused by low air or water supply to the pump or dirty filters.
- Not allowing the pump to stall properly when setting a prop.
- Extensions are not seated properly.
- Valves and seals are faulty.

Seismicity

A mine-wide seismic network (yielding locations with an accuracy better than 20 m) should be installed on all mines which experience rockbursts to facilitate the identification of hazardous areas, and aid the back analysis of rockbursts. The seismicity data should be carefully analysed to identify which parameters are most useful as indicators of increased rockburst hazard. The reliable and timeous prediction of rockbursts is a remote possibility at this stage.

Strong ground motion

Observations of co-seismic closure and ejection velocities provide useful parameters for the design of support. In one instance the mass of an ejected block and the evidence of a failed rebar enabled a minimum ejection velocity of 1,4 m/s to be estimated.

In most of the investigated rockbursts the dynamic closure was considerably less than the capacity of the support systems, and the bulk of the damage was due to disintegration of the rockwalls between support elements, rather than failure of the elements. This illustrates the importance of determining the stable 'dynamic span' for the support system and geotechnical area. It is important to realise, however, that if the containment support such as mesh and lacing is improved, a much greater dynamic load will be imposed on the bolts or tendons and their inadequacies would become evident.

Preconditioning

Several of the rockburst investigations were conducted at sites where preconditioning was being implemented. These investigations supported the view that preconditioning reduces the hazard of face bursts. It is important, however, that production personnel adhere to the preconditioning guidelines. As the effectiveness of preconditioning is believed to diminish with time, intervals between face-parallel preconditioning blasts should be based on the elapsed time, not merely on the face advance.

Conclusions

Why does the severity of rockburst damage vary so much? There is no single, simple answer. Probably the most important reasons are variations in the condition of the rock mass and the failure of inadequate support systems. Neither is there an easy, instant solution to the rockburst hazard. Given the current methods of mining, the most important steps to be taken to reduce the rockburst hazard would involve frequent inspections of working places by personnel able to identify changes in the rock mass condition and recommend and implement appropriate changes to layout and support systems; discipline in ensuring that support is always up to standard and that the stope support system is as close to the face as possible; and adherence to sound layouts regardless of the demands of production.

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