Simulated rockburst experiment—evaluation of rock bolt reinforcement performance

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Synopsis

Detailed monitoring of the response of the rock mass between rock bolt reinforcement units subjected to a simulated seismic source has been successfully conducted. This work has shown the increase in amplification of the Peak Particle Velocity (PPV) with distance from a rock bolt unit, and, a minimum PPV for rockburst damage for the given site characteristics. This understanding, at this site, will allow the design of a suitable rock bolt spacing to prevent unravelling of the rock mass between the rock bolt units for a given level of seismicity. Or, alternatively, an estimation of the requirement for a suitable fabric support system, for the anticipated level of seismicity, can be made.

Introduction

Background

As part of a simulated rockburst experiment at a tunnel site at the Kopanang mine in the Klerksdorp gold field (Hagan *et al.*[1]), the influence of the rock bolt reinforcement on the response of the rock mass to dynamic loading was examined. The results will improve the understanding of the interaction between the rock bolt units and the discontinuous rock mass structure under conditions of dynamic loading, and, thus improve the design of tunnel support systems under these conditions.

Nature of problem

The condition of tunnels is influenced by the geological structure, the state of stress in which they are developed and changes in the local field stress due to adjacent mining of the orebody. In addition, the most dramatic influence can be due to the occurrence of a seismic event, which results in the rapid dynamic loading of the rock mass surrounding the excavation. If the event occurs in close proximity to the tunnel, then this loading may result in violent deformations of the rock mass and loading of the support system. It is this environment in which the current support systems are often found to be inadequate.

Performance of current tunnel support design systems

The design of tunnel support systems in the South African mining environment is currently based on a simple mechanistic evaluation (Anon.[2]). This design procedure is principally focused on the rock bolt reinforcement unit. The mechanistic design procedure evaluates the support resistance (kN/m^2) or energy absorption (kJ/m^2) of the rock bolt system based on tributary area loading for static and dynamic loading conditions respectively (Figure 1). In this mechanistic design procedure there is no allowance for the potential for rock mass deformation between the rock bolt units, and, thus, no account for the loading of the often-necessary fabric support systems. The requirement for fabric support systems is still often based on experience or empirical design methodologies and incorporated with the mechanistic design of the rock bolt system. The requirement for energy absorption within the support system design is accommodated by the need for yield capability of the rock bolt system. The length of the rock bolt units is selected to allow sufficient anchorage beyond the anticipated depth of instability as typically derived from analysis of an historical accident database (Anon.[2]). The spacing of the rock bolts is defined by their capacity in relation to the anticipated tributary area loading.

The application of this support design methodology has been shown to be inadequate in capturing the performance of the implemented support systems, particularly under highly discontinuous rock mass conditions and dynamic loading, Haile[3]. Under these conditions it has been observed that the

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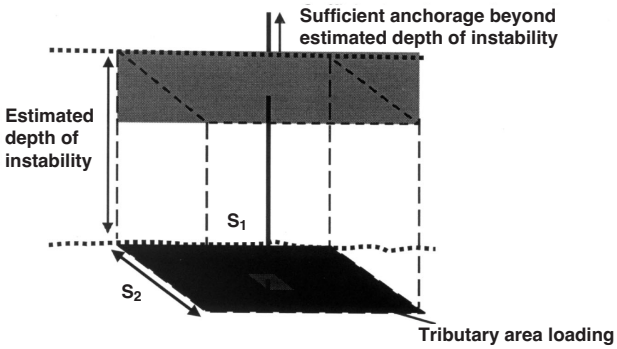

Figure 1—Mechanistic design of rock bolt support system based on tributary area loading

rock mass is prone to unravel between the rock bolt units resulting in either the failure of the excavation or the significant bulking of any mesh and lace fabric support. Associated with this bulking of the fractured rock mass is the lower direct loading of the rock bolt units and the often observed survival of relatively 'stiff' rock bolt systems under severe dynamic loading.

These factors may explain the poor utilization of yielding support within the deep level South African mining environment. Although the current design is conservative in nature with regard to the loading of the rock bolt system, it does not capture the necessity for the fabric support. The fabric support is often observed to fail in preference to the rock bolt system with limited load transfer from the fabric to the rock bolt anchorage. The lack of failure of these rock bolts is perceived to negate the necessity for the implementation of rock bolt yield capacity.

Instrumentation and monitoring

The effectiveness of the rock bolt reinforcement in influencing the dynamic response of the rock mass and containing potential rockburst damage was the focus of this aspect of the investigation. The monitoring programme and instrumentation to evaluate this included measurement of the area and volume of damage, and the use of geophone arrays between rock bolts (Figure 2) to measure the stable response of the rock mass.

Mapping of the rock mass structure was also conducted prior to the experiment in order to classify the rock mass at the skin of the tunnel. Mapping of the rock mass indicated the average bedding plane separation, in the vicinity of the instrumentation, to be approximately 50 cm, with bedding planes dipping at 30° in the plane of the sidewall. Stress fracturing associated with the development of the tunnel was approximately vertical, generally open up to 2 mm and at a spacing of approximately 10 cm along the axis of the tunnel. The stress fracturing made an angle of approximately 20° with the sidewall of the tunnel creating wedge shape blocks within the rock wall.

Results

The results discussed in this section refer specifically to those related to the performance of the rock bolt reinforcement system.

Overall tunnel response

Prior to the simulated rockburst the tunnel sidewalls were whitewashed and the footwall cleaned to allow easy identification of subsequent damage due to the simulated rockburst. The damage to the excavation is illustrated in Figure 3 by the exposed (darker) areas on the sidewall and the ejected rock mass on the footwall.

The distribution of damage to the sidewall, as reflected by the volume of rubble on the footwall, per metre of tunnel length is shown in Figure 4. There is a clearly defined area of high intensity damage over a tunnel length of approximately 10 metres. This area is located adjacent to the estimated position of the blastholes, which formed the simulated seismic source. Away from this zone, in advance of the end of the blastholes, minor damage was observed over a further 10 metres. In no case was there failure of the rock bolt reinforcement. The blocks that were ejected from the rock wall were defined by the pre-existing discontinuities. The length of the blocks, as delineated in the sidewall rock mass varied between 40 cm and 80 cm, the width varied between 30 cm and 50 cm as defined by the bedding separation, and the thickness was approximately 15 cm as defined by the stress fracturing. The maximum block volume was approxi-

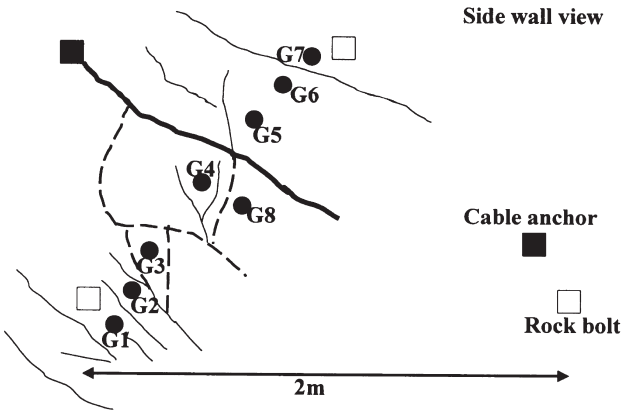

Figure 2—The array of geophones between the rock bolt units and an indication of the exposure of the rock mass structure on the sidewall of the tunnel

Figure 3. Photograph showing rockburst damage along the experimental tunnel. The area of high intensity damage is in the foreground and low intensity damage towards the background

mately 0.07 m³. All the damage was confined to the sidewall adjacent to the simulated seismic source.

From the array of accelerometers and geophones along the length of the experimental tunnel section the limits of high and low intensity damage could be correlated to minimum PPV that caused the defined intensity of damage of approximately 1.6 m/s and 0.7 m/s respectively (Figure 5). It is important to note at this stage that these velocities were recorded at approximately the midpoint between rock bolt units. The PPV of 0.7 m/s also corresponds to the minimum ejection velocity as determined from the analysis of ejected blocks captured by the high-speed camera at this site.

Local rock mass response

The array of geophones between the rock bolts, as discussed previously, was located at approximately 39 m from the reference point used in Figures 4 and 5, and thus outside the area of observable damage. The data from this site clearly illustrated an influence of a rock bolt reinforcement unit on the dynamic response of the local rock mass. The response of the rock mass in relation to a rock bolt reinforcement unit is shown in Figure 6.

Figure 6 clearly illustrates the general trend of increased PPV with increased distance from the rock bolt reinforcement. The data point at approximately 36 cm from the rock bolt is anomalous to the general trend and considered to be due to the inherent variability in the rock mass. This behaviour of increased PPV with distance from the rock bolt is in accordance with measurements at other tunnel sites under conditions of natural seismicity (Haile *et al.*[4],). Increased amplification of PPV has been shown to be associated with the fracturing around an excavation, and, thus, increased discontinuity of the rock mass (Durrheim *et al.*[5]). The influence of the rock bolt reinforcement is to maintain a higher degree of interaction and inherent strength within the rock mass. This will thus reduce the potential for amplification of peak ground velocities. With distance away from the rock bolt unit the discontinuous rock mass is under reduced reinforcement and thus increased degree of freedom. *In situ* observations of rockburst damage (Haile[3]) have shown this reduced retainment of the rock mass away from the rock bolt reinforcement to result in substantial rock mass unravelling under severe dynamic loading.

The intensity of measured rockburst damage also confirmed the relationship associated with the distance from the rock bolt reinforcement and in addition showed increased damage with the increased level of dynamic loading as reflected by the PPV (Figure 7). This evaluation was based on the area of ejection around a rock bolt unit as a percentage of its tributary area. Again the tendency for increased damage to the rock mass with increased distance from the rock bolt unit is shown. Comparison of the areas of high and low intensity damage indicates the increased rate of rock mass unravelling with increased dynamic loading.

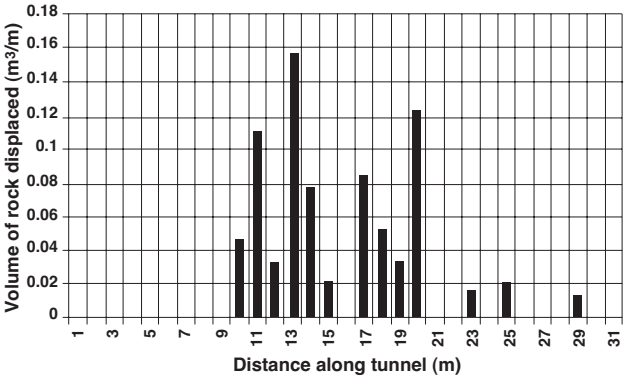

Figure 4—Distribution of rockburst damage (expelled rock mass) along the length of the experimental tunnel

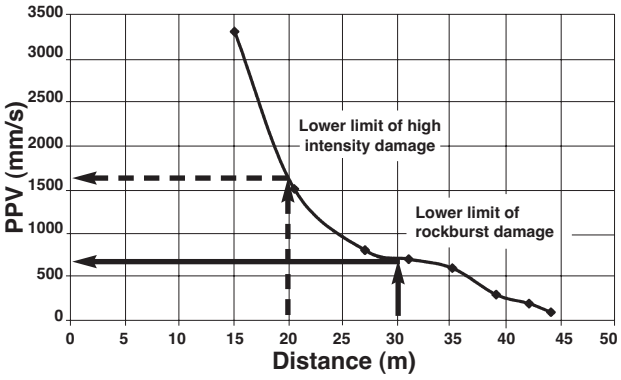

Figure 5—Measured PPV distribution along tunnel axis with indicated limits of high and low intensity rockburst damage. It is noted that these values were measured at approximately the mid-point of rock bolt pattern

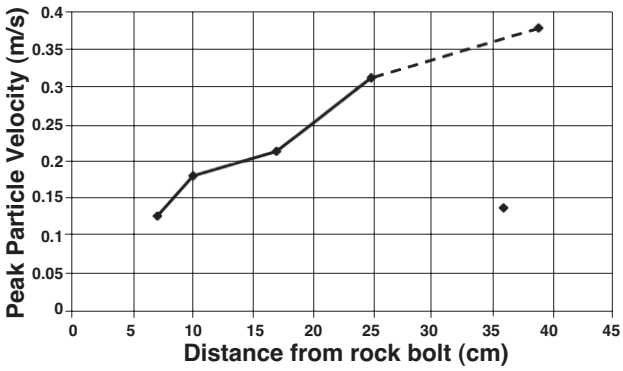

Figure 6—*In situ* relationship between PPV and distance from a rock bolt reinforcement unit

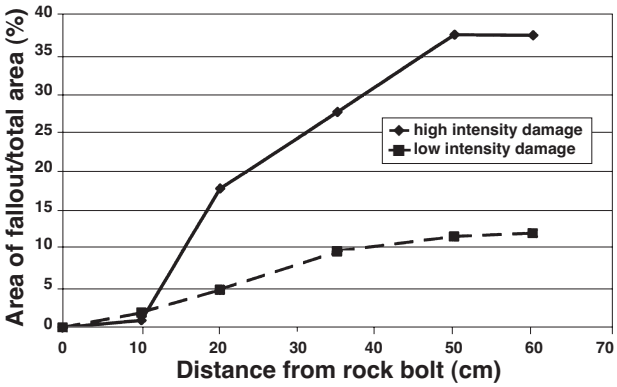

Figure 7—*In situ* evaluation of damage distribution around rock bolt reinforcement units due to the simulated seismic source

However, in the immediate vicinity of the rock bolt, probably where there is direct interaction between the rock bolt unit and the rock mass, minimal damage occurs even under the higher levels of dynamic loading. The blocks ejected were defined by the pre-existing structure of the rock mass, as discussed previously.

Numerical modelling of rock bolt reinforcement interaction

In an attempt to mechanistically evaluate the interaction between rock bolt reinforcement and the rock mass under dynamic loading, numerical modelling using the Universal Distinct Element Code (Anon.[6]) was conducted. In this exercise it was not attempted to quantify the influence of the rock bolt unit in terms of absolute PPV values, but to qualitatively capture the mechanism of PPV amplification with distance from the rock bolt. Figure 8 summarizes the relationship between the PPV and distance from the rock bolt reinforcement for the numerical model.

It is clear from the comparison of the trend in Figure 6, for the *in situ* data to that of Figure 8, for the numerical data that a similar characteristic response to the dynamic excitation is exhibited i.e. PPV increase away from the support units. A comparison of the magnitude and rate of amplification of PPV is clearly different, as the *in situ* rock mass properties, structure and the third dimension of the problem are not captured in this numerical evaluation.

Discussion and conclusions

Evaluation of the results of this aspect of the simulated rockburst experiment clearly indicates the concept that in a discontinuous rock mass environment there is a limited interaction between the rock bolt reinforcement and the rock mass at the boundary of the excavation. This unstable rock mass volume, under dynamic loading, will define the demand on the typical mesh and lace fabric support systems (Figure 9). This in turn would allow an estimation of the required capacity of the fabric system. It also implies that the direct loading of the rock bolt reinforcement will be reduced in comparison to the current assumption of tributary area loading. This may be highlighted by the measurement of peak ground velocities up to 3.3 m/s (Figure 5) and observation of block ejection velocities up to 2.5 m/s at this site without failure of a single rock bolt unit (Milev *et al.*[7]). The survival of these relatively stiff rock bolt units under severe dynamic loading has also been observed at numerous rockburst investigations (Haile[3]). It may also indicate that these high ground velocities are only associated with the skin of the excavation and decay rapidly into the more reinforced rock mass.

It has been proposed by (Haile *et al.*[4]) that the inability of the current design process to capture these deformation mechanisms may explain the lack of acceptance of the necessity for yielding capacity of the rock bolt, based on the current design philosophy. However, where stiffer fabric support systems that interact directly with the rock mass are used, recent work based on numerical modelling (Haile *et al.*[4]) has also shown that rock mass unravelling will be greatly restricted. This will in turn result in increased direct loading of the rock bolt unit, with the necessity for increased energy absorption capacity within the rock bolt component of the support system.

It is considered that the following conclusions of this aspect of the simulated rockburst experiment have added to the improved understanding of the performance and design of rock bolt reinforcement systems in highly discontinuous rock mass conditions.

It was shown through underground measurements that there is an increase in PPV with distance away from a rock bolt reinforcement unit. This implies the effectiveness of rock bolt units to reinforce and confine the rock mass in its immediate vicinity, but that there is an increased potential for block ejection and rock mass unravelling with increased rock bolt spacing.

A minimum PPV on the skin of the excavation of 0.7 m/s defined the extent of rockburst damage for the site rock mass and reinforcement characteristics. This understanding would allow the design of rock bolt spacing, at this site, to prevent rock mass unravelling for an anticipated dynamic loading condition based on the derived relationship between rock bolt spacing and PPV amplification.

- The relationship between measured rockburst damage with distance from the rock bolt reinforcement and level of dynamic loading (PPV) has been clearly illustrated. It is this potentially unstable rock mass volume that will define the demand on, and thus the capacity of the typical mesh and lace fabric support systems.

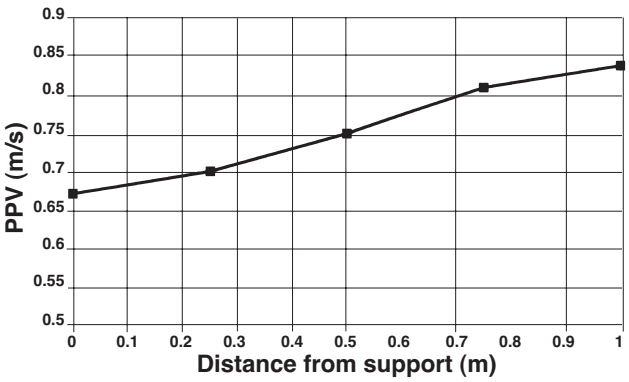

Figure 8—Numerical relationship between PPV and distance from a rock bolt reinforcement unit under dynamic excitation

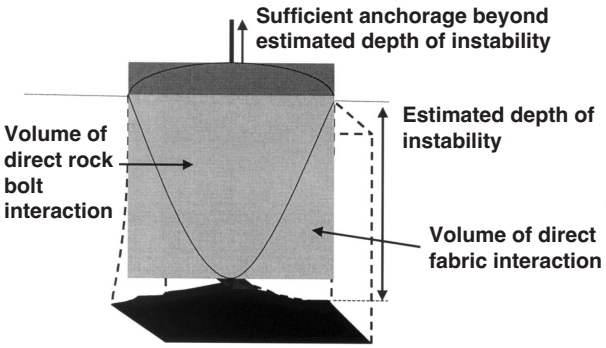

Figure 9—Conceptual model of the interaction between a rock bolt reinforcement unit and a discontinuous rock mass structure under conditions of rock mass retainment

In addition the planning of future measurements of PPV in the vicinity of excavations must consider the relationship between the location of the monitoring site and the proximity of any support components. This would be applicable to internal rock mass reinforcement such as rock bolts in tunnels, and also to typical stope support systems such as packs or elongate type, external rock mass support components.

Acknowledgements

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Minquiz—A history*

In 1988, Mintek introduced a science quiz (Minquiz) for the 50 senior schools within a 12 km radius of its Randburg premises, extending the radius a few years later. The larger area embraced about 70 senior schools, including those in the residential area of Alexandra.

The aims of Minquiz are to encourage interest and careers in science, engineering and technology (SET) especially in the minerals field, and to promote an awareness of the importance of minerals to South Africa. From the beginning, an important feature of Minquiz was the conducted tours of Mintek's laboratories and pilot bay facilities.

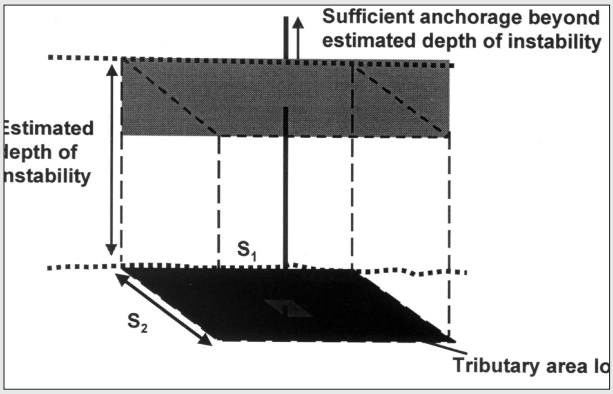
Between 1993 and 1998, Minquiz became a national event as additional centres were recruited to run the regional Minquiz competitions. The University of Pretoria was the first to duplicate the event in 1993, and lastly, Rustenburg came on board in 1999. In the intervening years regional organizers emerged at the University of Natal, University of Cape Town, University of Port Elizabeth, University of the Free State, Iscor Sishen, Consolidated Metallurgical Industries at Lydenburg, and the Pietersburg College.

The underlying rationale behind the competition is that it should be FUN for participants, accompanying teachers, and audiences, while at the same time serious messages should be conveyed.

The emphasis is on teamwork, with three Grade 12 pupils from a school functioning as a team. In both the Regional and National Final events, the teams undergo a preliminary written quiz before a limited number of teams progress to an oral on-stage final quiz.

Minquiz is extremely popular with pupils, and especially with their science teachers. Each year some 350–400 schools are involved nationwide. The effect on 1000 learners each year is significant and the beneficial effects are of a more lasting nature for the 500 or more teachers that attend.

Over the years Minquiz has proved to be an effective vehicle for promoting SET in South Africa. It is, after all, a rare link between the best of South Africa's senior schools and SET careers. The high degree of involvement of universities at the regional organizational level amply demonstrates that these institutions recognize the high value of such a link.



Members of the victorius Gauteng South team, Nadine Moonsamy (Lenasia Secondary School), Rex Green (Trinityhouse High School), and Dimitri Vlachos (Hoërskool Noordheuwel) celebrate with Mintek CEO, Dr Paul Jourdan

Thirty schools were represented in the final competition, three from each province, (two from Gauteng); and five provinces, Gauteng North, Gauteng South, Eastern Cape, North West, Free State, progressed to the final oral quiz after a tough written quiz.

The winning team, comprised of one learner each from Lenasia Secondary School, Trinityhouse High School, and Hoërskool Noordheuwel. Each jubilant team member was awarded with a cheque for R10 000 to take back to their school.

This year, Minquiz has received financial support from Anglo Platinum, De Beers, Degussa, and Billiton. ◆

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