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Reinforcement selection for deep and high-stress tunnels at preliminary design stages using ground demand and support capacity approach

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ABSTRACT

Underground mining is going to be deeper gradually because near surface resources are going to be depleted. Therefore, risk of seismic events in underground mines is escalating. Additionally, existence of the large ratio of horizontal to vertical stress, could be a potential reason for high-stress condition and occurrence of dynamic activities. Depending on various parameters such as the level of induced stress, rock properties, etc., ground demand changes and it is difficult to estimate. On the other hand, under seismic condition, energy dissipation and deformation capacity of supports is the most important factors, however, rock support performance factors in dynamic conditions are still under investigation. Expanding the knowledge of reinforcement behaviour and capacity, specifically that of the rockbolt as a primary element in seismic conditions, would help to develop a suitable, safe and economic support design. This paper contains various methods to estimate ground demand including the intact rock properties approach, failure thickness and ejection velocity estimation, and rockburst damage potential method. It also covers measurement methods of rockbolts energy dissipation capacities such as drop test, blasting simulating, back calculation and momentum transfer measurement methods. A large-scale dynamic test rig is also explained. Based on the findings, a table and a graph to show the applicable range of each type of rockbolts were presented. Suitable rockbolt types for various ground energy demand and deformation capacity range were categorised in the table and the graph. The presented support selection method facilitates the selection of a suitable reinforcement system at the preliminary stages of design and guides the designer to adjust the support reinforcement system based on observed ground and support reaction.

1. Introduction

Deeper underground mining exploitation is increasing worldwide because near surface mineral resources become gradually depleted. In-situ stress increasing in rock is the main difference between rock stresses at depth compared to the rock near the surface, and dynamic activities are direct consequences of such a condition. Seismic events such as the rockburst might occur below 600–800 m depth and more likely passing 1000 m depth. Such phenomena are not limited only to deep mines as many shallow mines in Australia experience such events due to the presence of high horizontal to vertical stress ratios.

Hard rock mining is experienced at a depth of about 2 km in Australia, more than 3 km in Canada, and a depth of about 4 km in South Africa highlight the importance of ground stability at such depths. Finding a practical support design requires determining the rockmass energy demand and rock support energy dissipation capacity. Numerous unknowns, uncertainties in geomechanical parameters and randomness occurrence of seismic events increase the complexity of the rock demand determination and consequently extend the complication of an effective support design.

Though a significant amount of work has been done to estimate energy dissipation capacity of support elements, this subject is not much known. Additionally, the role played by other mechanisms of loading, like dynamic shear loading, in the support system is also not clearly understood.

To achieve stability and safety at deep and rockburst prone conditions, appropriate support and reinforcement design is necessary. The support system should not only be able to tolerate the static rock load and potential dynamic load due to induced stress, but it should also not lose strength over a wide range of deformation. It could be concluded that the energy dissipation capacity of support elements individually, as well as the ground support as an integrated system, needs to be found. Ground energy demand cannot accurately be determined or calculated, but some

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estimation might be achieved to help engineering judgment. Some of the methods, based on intact rock properties, have attempted to find a relationship between rockmass properties and their potential to burst, and the real condition of rockmass under stress [1,2]. Some other methods are based on the estimation of probable failure volume, ejection velocity and the travelling distance of ejected materials [3]. Another recent method relies on the definition of the effective parameters on the potential of rockburst and its likely damage [4]. On the other hand, some researchers believe that there is not a precise method to determine rockmass demand with any degree of confidence [5].

Along with ground demand during dynamic events, much effort has been expended in determining the rock support energy dissipation capacity. Rockbolt as the primary element to transfer the energy of the displaced volume of surface rock to the ground in depth has been the focus. Several approaches including the drop test, blast simulation, back calculation and momentum transfer method have been developed in order to examine rockbolt performance [4,6–10]. Another so-called large-scale dynamic test rig has been constructed in 2012 by Geobrugg in Switzerland in order to investigate the whole support system as an integrated system [11,12]. Despite several research studies on different ground types, support systems in a wide range of loading, rockbolt types, etc., there are limited comprehensive studies on this subject.

In this research, at first, a short explanation of different mechanisms of rockburst and rock ejection and various methods of ground demand estimation and rockbolt energy dissipation capacity, are illustrated. Then, suitable rockbolt type selection is recommended for different ground demand levels. The method is simply presented by table and graph which is easy to use in practice. The presented methods can assist the selection of appropriate rockbolt type at the preliminary stages of mine design. Additional to the rockbolt selection, some further considerations for the selection of other support elements is given as well.

2. Deep underground and high-stress mining

Seismically active underground mines are those which are prone to dynamic rockmass failure. As mining progresses, the natural stress equilibrium of the rockmass is disturbed. Stresses concentrate around the edges of an excavation or in pillars of rock between excavations left unmined for support, due to low grade or other reasons. Stress may also be increased or relaxed on preexisting planes of weakness such as faults, shears or lithological contacts. These stress changes cause the accumulation of potential energy in the unmined rock. This energy may be gradually dissipated, or it may be released suddenly during the process of inelastic deformation and radiates detectable seismic waves.

2.1. Ground behaviour in seismic conditions

Rockmass varies from massive, layered and jointed to heavily crushed conditions. In addition, dynamic loading has a broad range of frequency, amplitude, and wavelength. Therefore, ground behaviour varies widely considering the rockmass and dynamic loading conditions. The most common types of strain burst and seismic failure mechanisms in different ground types are categorised into four primary ejection types based on various factors as shown in Fig. 1.

Fig. 1a shows the mechanism of strain burst during ejection of a volume of rock due to stress concentrations or induced stresses. In this condition, discontinuities have a minor effect on ejection, so it is difficult to predict the volume of rock to be ejected and even sometimes the likelihood of an ejection.

Fig. 1b shows the ejection of a volume of rock by the mechanism of sudden buckling or spalling of rock in the wall or even in the face due to induced or concentrated stress on the boundaries of the opening where foliation of the rockmass is nearby vertical. This mechanism applies to strong to extremely strong rocks.

Fig. 1c shows the ejection of a volume of rock in the wall due to a seismic event near the boundaries of a stope or a tunnel which is due to slip or energy transfer on an adjacent discontinuity. Initial or secondary discontinuities can bound the volume of ejection so it can be estimated if the location of such an event is known.

Fig. 1d depicts the mechanism of instability in the back due to a combination of the effect of loosening of discontinuous blocks, gravity, and/or a seismic event. Loosening of the blocks in the back could be a result of the lack of enough confining stress or previous blasting. The seismic event can accelerate the phenomenon under the effect of available gravity.

Therefore, considering the wide range of rockmass and dynamic load conditions, various types of failures such as spalling, rock ejection and block fall can be expected.

2.2. Ground seismic energy demand

When a dynamic load propagates in the excavation, rock deformation occurs and cause an energy release. Estimating the magnitude of released energy is important to design a suitable reinforcement system. Although several methods have been developed to estimate the ground energy demand, they can be categorised into three groups namely, Intact rock property approach (IRPA), Estimation of failure volume and ejection velocity, Rockburst damage potential. A brief illustration of each method is given in the following subsections.

2.2.1. Intact rock property approach (IRPA)

When a volume of energy that should be tolerated within the rockmass exceeds its capacity (Strength), sudden failure happens, and energy is quickly released. Although all factors such as discontinuities and their infilling material properties, and the presence of underground water and its effects are important, intact rock properties have significant roles in this phenomenon. As a matter of fact, the intact rock energy absorption capacity could determine the upper limit of energy absorption capacity or in other words, the potential releasable energy of the rockmass. Some criteria have been defined to estimate the potential of rockburst based on intact rock properties including Index of strain energy, Potential energy of elastic strain [1,13], rock brittleness [14], and ratio of tangential stress to compressive strength [15].

An excess of energy during the post-peak deformation stage conclude in violent rock fracturing [16]. Energy release rate (ERR) has been developed as a basis for mining exploitation pattern design. Rock subjected to the compression process experiences elastic and plastic deformation. Elastic deformation (strain) of the rock can be recovered if unloading occurs before peak strength. At brittle failure, the elastic strain releases suddenly and causes a rockburst. Therefore, by applying a cyclic compressive strength test, the energy storage capacity of rock can be estimated. As it is shown in Fig. 2a, Φds is the portion of energy which is dissipated due to initiation and propagation of micro-cracks in the rock sample (plastic deformation). Φel is the portion of energy which is consumed for elastic deformation and stored in the rock. This portion of energy stored during the loading process up to point A could be released gradually by unloading or suddenly by failure. The ratio between elastic strain energy and dissipated energy (index of strain energy) could be used as a criterion or an indicator of rockburst potential.

$$F = \Phi el/\Phi ds \tag{1}$$

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