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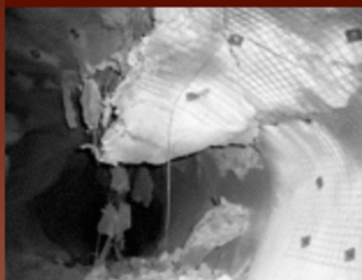


ROCK MASS RESPONSE TO MINING ACTIVITIES

INFERRING LARGE-SCALE ROCK MASS FAILURE

TADEUSZ SZWEDZICKI

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Inferring Large-Scale Rock Mass Failure

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Cover illustrations:

Photo top left: Damage to the hangingwall at the shoulder of a squat pillar.
Photo top right: Pillar punching the roof.
Photo bottom left: Sinkhole, Warrego mine (1989).
Photo bottom right: Asymmetrical closure of a crosscut due to approaching caving front.

All photos by T. Szwedzicki

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Preface

The concepts covered in this book offer significant benefit to professionals with expertise in geotechnical engineering, mining engineering and/or geology aiming to understand rock mass behaviour associated with mining activities.

To predict a geotechnical event in a mine, it is critical to specify type of damage, location of damage, severity and time. This book focusses on two elements: (1) inferring type of damage and (2) specifying location of potential damage.

The case studies presented in the book demonstrate that in all cases the severities of geotechnical mining disasters were unimaginable (numerous fatalities and loss in billions of dollars), and that timing of the events depended on internal or external triggers which were seldom predictable.

The book discusses geotechnical indicators and warning signs of impending or progressive damage, collapse or rock mass failure which together with analysis of mining parameters could provide guidelines for prevention or mitigation of damage to mining excavations.

After finishing the book, you should be able to read rock mass behaviour and should be able to detect the tell-tale signs of impending rock mass damage.

T. Szwedzicki

About the author

Dr Tadeusz Szwedzicki is an internationally recognised expert in geomechanics of underground mining methods. He has over 40 years of mining experience working in mining production, research and development, and consulting. His experience has been gained working for some of the world's largest mining companies like PT Freeport (Indonesia), ZCCM (Zambia), Anglo American Corp (Republic of South Africa), and WMC and BHP Billiton (Australia). He held academic positions at Western Australian School of Mines, Curtin University of Technology and University of Zimbabwe. His experience includes government position at the Northern Territory Department of Mines and Energy where he was appointed the Government Mining Engineer. He also worked for the Government of Papua New Guinea as Mineral Resources Advisor. He is a recipient of the Silver Medal awarded by the Institution of Mining and Metallurgy, London, and a recipient of a Fulbright scholarship, USA. He has authored over 70 papers including in the *International Journal of Rock Mechanics*, *Transactions of the Institute of Mining and Metallurgy*, and proceedings of international conferences. He is an independent consultant specializing in geomechanics of mining methods.

Chapter 1

Introduction

> All failures resulting from human activities are predictable.
>
> anonymous

Just a few days after I started working at a deep underground hard rock mine as a geotechnical engineer, a double fatality happened. Two miners carrying a heavy pump up a decline were killed by a rockfall. Investigation that took place described the accident as "unpredictable" and stated that the support was adequate for the prevailing conditions. One day, soon after the rockfall, when I was walking up the decline, I noticed that at that particular spot there were some wet patches at the back and some water trickling at one sidewall. After a few walks, I noticed the width of the decline was about half a metre wider than in other places, which wasn't clearly visible because of irregular walls caused by blasting. After thorough inspection, I realised that the rockfall was in a fault zone. The rock mass within the fault (which was about 5 m wide) was similar to the neighbouring country rock but was highly jointed. All these observations made me think if that rockfall was really unpredictable. That accident was a reminder that the paramount objective of mining geomechanics is to ensure safety of mining personnel. This marked the beginning of my geotechnical quest – to determine whether we are in fact capable of reading the signs of rock mass response to mining . . . and therefore, predicting potential geotechnical hazards such as failure of rock around mining excavation or even potential disasters like ground collapse, rockburst or inundation?

My quest has been pursued globally in mines in Europe (Poland), Africa (Zambia, Zimbabwe, Republic of South Africa), and Australasia (Papua New Guinea, Indonesia, and Australia).

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Identification of mining geotechnical hazard shall be based on observations and monitoring of rock mass behaviour under mining-induced stress and on analysis of mining parameters. This book deals with the challenge and covers two intertwining topics: factors governing rock mass response to mining activities and rock mass behaviour before, during, and after failure of rock and rock mass. These two topics are supported by numerous case studies and by discussion on modes of rock and rock mass failure.

Various manifestations of rock mass behaviour as response to mining can be identified in all phases of mining activities i.e. during development work and during production activities in stopes (Chapter 2).

A number of case studies are reviewed on large-scale failures and disasters in underground mines and open pit mines, on instability of tailings dam and waste material dumps and on inundation of mining areas. The reviews of the case studies are focused on rock mass response during the progressive damage, failure and post-failure rock mass response. The case studies on underground mining, in Chapter 3, include the following:

- surface crown pillars collapse above underground mining excavations,
- rockbursts, gas outbursts and geothermal outburst,
- uncontrolled caving and pillar collapse, and
- damage to underground infrastructures (large excavations, accesses and shafts).

Chapter 4 provides case studies on slope failure in open pits, including the following:

- failure due to underground mining below,
- failure along geotechnical structures, and
- collapse of a highwall.

Inundation and liquefaction are presented in Chapter 5 for the following:

- water inrush into a colliery,
- tailings inrush into an underground mine,
- backfill liquefaction and inrush,
- mud inrush following pillar collapse, and
- instability of waste rock dumps and tailings dams.

Damage can be stress induced or structurally controlled (or in a prevailing number of cases a combination of these). However, the fracture propagation that is caused by stress increase is instigated on microfractures. The detection and their effect on rock sample mode of failure is discussed in Chapter 6.

The ability to recognize pre-failure rock mass behaviour may result in predicting and averting the potential for geotechnical damage. Precursors to mining failures (like indicators, warning signs and triggers) are reviewed in Chapter 7.

Chapter 8 covers rock mass response at the onset of failure and duration of failure process. The chapter also provides case studies of progressive damage.

After failure the rock mass exhibits residual post-failure behaviour. The behaviour can be re-occurring and can last a long time. This must be considered when re-entering affected areas i.e. for post-event recovery or continuation of mining, as discussed in Chapter 9.

Modes of rock sample failure and modes of rock mass failure on local and mining scale are reviewed in Chapter 10.

Behaviour of fragmented ore and waste rock can affect rock mass response to mining. Rock mass fragmented after blasting may provide confinement to the surrounding rock mass. Compacted broken rock can transfer stresses that may result in ground deterioration around drawpoints and crosscuts, as discussed in Chapter 11.

Case studies demonstrate repeatedly that observation of rock mass response and timely implementation of ground control practices can mitigate the effect of stress changes leading to damage. However, the critical mitigation factor is the implementation of geotechnical quality assurance, as discussed in Chapter 12.

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Mining activities result in change in mining-induced stress. Changes in stress around mining excavations result in changes in the behaviour of the rock mass, which in turn may lead to mining disasters due to damage, failure and consequent collapse of the rock mass. Mining disasters may result in multiple fatalities, environmental damage and severe financial losses. The type and scale of response depends on *in situ* and mining-induced stress, structural features and rock mass strength, as well as mining geometry and the scale of mining operations.

Once the first signs of stress are observed, such as, cracking or fracturing of rock mass or damage to ground support, the excavations start to deteriorate. Damage to the rock mass can pose various geotechnical hazards like collapse of ground (fall of ground, crown or protective pillar collapse), seismic activities, slope instability, and inundation or instability of backfill, mine tailings or waste rock. The deterioration can progress linearly or exponentially i.e. deterioration begins slowly but then accelerates towards eventual closure or collapse. Rapid and violent failures of large-scale geotechnical mining structures cause significant safety hazards, material damage and interruption to or even cessation of mining activities. It is vital to acknowledge that all mining companies are vulnerable to such geotechnical events.

In small mining operations in low-stress environments, the rock mass response is hardly visible and such excavations have a very long life. However, with larger mining operations, especially in deep mines, the response can indicate mining-induced geotechnical hazards. Each rock mass failure is preceded by a precursory manifestation of rock mass behaviour.

Analysis of case studies shows that the rock mass responses can escalate in scale and finally end up in progressive damage, failure and/or collapse. Response to change of stress around mining excavations can be noticed long before failure. During the failure, different modes of rock mass failure take place and, finally, there is post-failure (residual) behaviour. Assessment of post-failure behaviour is required when making a decision on the timing of entering rescue teams, continuation of mining operations near affected areas, and even the surface utilization of a collapsed mine.

Ability to recognise indicators and warning signs may result in predicting or averting the potential for geotechnical failure and thus avoiding substantial losses. Unfortunately, precursors are not always recognised before the occurrence but are rather recalled in hindsight, during investigations into the disasters. In many occurrences, geotechnical failures were classified as “accidental”, “occurrence without precedent”, “sudden failure without warning”, “never anticipated or foreseen” or “unexpected” – yet on scrutiny were found to be not completely unpredictable. Instead, they could have been averted or at least the effects of failure could have been mitigated. Such failures often exceed engineering expectations of rock mass behaviour due to the large scale and severity of damage, which may be one of the reasons why they were often considered unexpected.

A variety of deficiencies may arise during the planning and design stages, and the most common are caused by incorrect siting of the development and by designing excavations of inappropriate size and shape. Damage to rock mass structures like pillars, stopes, chambers, magazine and secondary developments could be progressive or violent and may end up in closure or collapse. Mining history has clearly demonstrated disasters involving the collapse of pillars due to high extraction ratio, water or tailings inrush into mines as a result of the incorrect siting of surface water reservoirs and tailing dumps. Shafts have been abandoned because of damage to linings due to deformation caused by the unsatisfactory design of the shaft pillars.

When rock mass failure is accompanied by substantial uncontrolled rock movement, it is referred to as a collapse, for example, discontinuous subsidence, caving, rockfalls, slope instability or pillar disintegration. If rock mass failure is accompanied by an abrupt large energy release, it is referred to as a rockburst. If accompanied by abrupt large gas release, it is referred to as a gas outburst. When accompanied by a large increase in water inflow, it is referred to as inundation.

In large tailings dams or waste rock dumps, the failure takes place by slippage or flow of liquefied material. This is referred to as waste material instability.

Even with all the indicators and warning signs, mining companies seldom see the geotechnical failures coming. Even the most sophisticated and well-managed operations are frequently caught unaware by disastrous events – events that could have been anticipated and prepared for.

Anticipating and avoiding geotechnical events requires understanding of rock mass response to mining activities. Failure to do so will leave a company vulnerable to potentially devastating events.

Chapter 2

Factors affecting rock mass response to mining

> Geotechnical failures are events that should be seen coming.
>
> anonymous

Understanding factors affecting ground behaviour and prediction of rock mass response allows for assessment of vulnerability of mining infrastructure and mineral extraction processes. Once rock mass responses to mining are identified and risks determined, it is possible to implement appropriate mitigation actions. Understanding and foreseeing rock mass response and behaviour is needed for the mine design process, to select mining methods and to apply ground control techniques to ensure safe and efficient mining practices.

The consideration deals primarily with rock mass response where damage around mining structures occurs and where confining stresses are very low or tensile.

Under stress (which can be mining-induced or externally triggered by blasting or seismic events) a rock mass is subject to damage. Although the damaged rock mass may transfer stress and maintains its integrity, there is always risk of failure and collapse. Geotechnical failure of mining structures is defined as fracturing or disintegration resulting in loss of bearing capacity and loss of ability to perform its function. Although rock mass failure process is a function of rock properties, structural features and mining geometry, the failure itself is driven by stress changes. The loss of bearing capacity happens because of uncontrolled ground movement or energy release. When failure is accompanied by substantial discontinuous displacement of rock, it is referred to as rock mass collapse. Another form of rock mass response is progressive deterioration. Progressive deterioration takes place when the rock mass behaves in a ductile way. During such deterioration excavations change their shape without failure i.e. are able to continuously transfer stress until such deformation is achieved that a new stress balance is achieved. Mode of failure is defined as a manner, form or mechanism of rock or rock mass fracturing leading to failure under induced stress.

2.1 GEOTECHNICAL FACTORS AFFECTING ROCK MASS RESPONSE

Factors contributing to rock mass response leading to damage are structural features and rock mass mechanical properties, and *in situ* and mining-induced stress (Fig. 2.1). The figure also incorporates the role of failure criteria and refers to ground control techniques. Rock mass response can indicate stability or instability. Stability refers to open span of

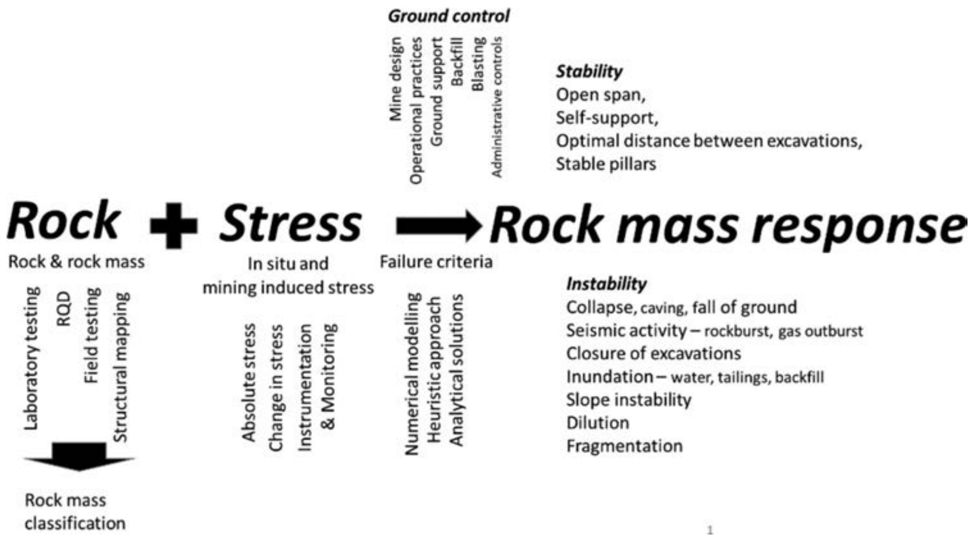

Figure 2.1 Geotechnical input to determine rock mass response.

excavations, self-support, optimal distance between excavations, stable pillars, etc. Instability, for example, can result in ground collapse, rock mass fragmentation, seismic activity, closure of excavations, slope movement, inundation, and failure of tailings storage facilities.

Two general modes of damage can be distinguished: structurally controlled gravity-driven and stress-induced failure with spalling or slabbing (or any combination of them). Structurally controlled modes of failures are most frequently observed at shallow depths, and stress-induced failure is commonly found at greater depth. At shallow depth, slip along discontinuities or shearing of the rock matrix dominates the failure process, while at depth stress-induced fracturing is most common (Kaiser, *et al*., 2000).

Mechanical properties are determined by laboratory testing of rock samples. Rock mass is described by the Rock Quality Designation/Fracture frequency number, field testing and structural mapping. All these factors allow for geotechnical classification of the rock mass (Brady & Brown, 1993). Blasting, stress fracturing and water often reduce rock mass properties in the vicinity of mining excavations. Rock mass behaviour, in each geotechnical domain, also depends on combination of often contiguous very poor and good ground domains. Large structural features like faults, folds and joints can control the mode of failure. However, damage is often instigated by stress concentration around microfractures (see Chapter 6).

2.2 MINING FACTORS AFFECTING ROCK MASS RESPONSE

Stress is considered as superimposed *in situ* stress and mining-induced stress and is determined by measurement of the absolute values of stress and by measurements of stress changes. Although *in situ* stress doesn't change during the life of a mine, the mining-induced stress changes during mining activities. Mining-induced stress depends on mining geometry,

geometry of mining excavation and compaction of fragmented rocks. Mining geometry, when referring to mine production, includes the extraction ratio, pillar width-to-height ratio, sequencing of extraction and ground control measures such as backfill or support. Geometry of mining excavations includes shape and open span, pillar size, interaction between neighbouring excavations, etc. When using caving, open-stoping or shrinkage methods, there is one more factor – broken rocks. Rock mass fragmented after blasting, when left in stopes, cave zones or orepasses, provides confinement to the surrounding rock mass that may be affected by abutment stress. Compacted broken rock can transfer stresses that may result in ground deterioration around drawpoints and crosscuts.

Failure criteria like numerical modelling, heuristic methods or analytical solutions determine if the rock mass is susceptible to failure i.e. its response results in stability or instability but is not used to determine the mode of failure.

Predicted instability is indicative of rock mass collapse, fall of ground, seismic activities, dilution, fragmentation and rock mass damage; when instability is foreseen, ground control measures such as appropriate mine design, ground support or backfill must be considered.

Various manifestations of rock mass behaviour as response to mining can be identified in all phases of mining activities. Damage to the rock mass can be described by defining the extent (local or mine scale), location of the damage (pillar, floor or back or larger scale), mode of failure (tension, shear or coupled) and rock mass response (brittle or ductile).

Rock mass response can be controlled during design and planning stage, development stage and production (Fig. 2.2; Szwedzicki, *et al.*, 2007).

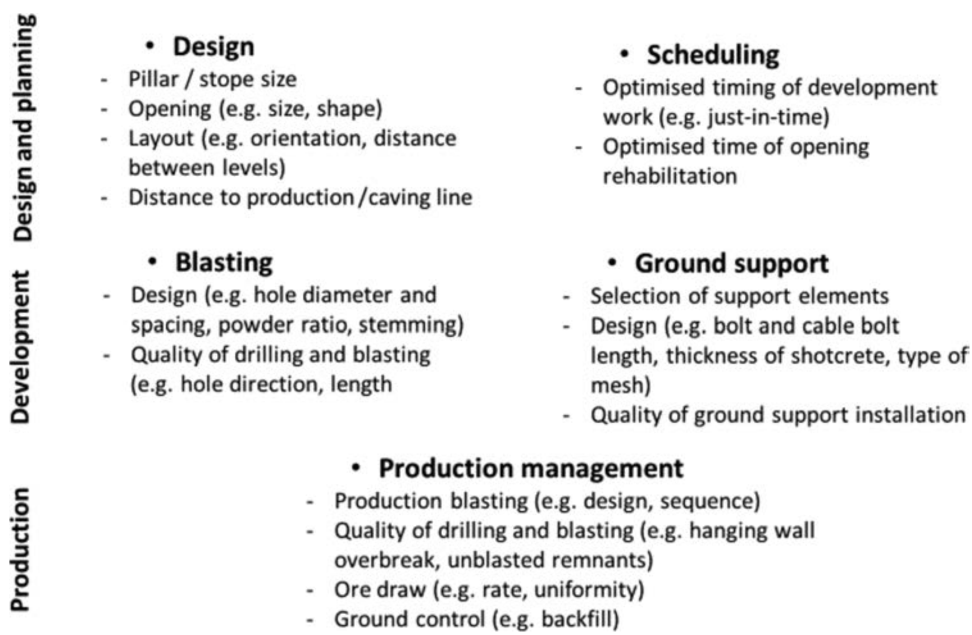

Figure 2.2 Mining factors affecting rock mass response (Szwedzicki *et al.*, 2007).