STRESS WAVE AND FRACTURE PROPAGATION IN ROCK

(Thesis Summary)

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ABSTRACT

In rock dynamics stress wave propagation and dynamic fracturing are important transient phenomena governing the stability and safety of geotechnical structures. In this thesis combined experimental and theoretical approaches are developed to study various aspects of the dynamic behaviour of rock. The work addresses specifically stress wave interactions with rock mass discontinuities and dynamic fracturing due to blasting.

The main topics dealt with are as follows:

(i) *Wave Interactions with Rock Joints*: An analytical approach is used to quantify the wave reflection and transmission characteristics of various rock joint types. These are described by interface conditions ranging from the well-known welded and frictionless interface, to new discontinuity types modelling friction, cohesion, joint stiffness related to measurable material properties, undulating joints and dissipative interfaces.

(ii) *Wave Interactions with Excavations*: Experimental and numerical techniques are used to investigate the dynamic stress field resulting from cavity – wave interactions. Plate model experiments are utilised to visualise the complex interaction process, and numerical simulations are conducted to investigate energy channelling, dynamic stress intensification and mechanisms governing stress wave driven fracturing in the excavation vicinity.

(iii) *Blast Induced Fracturing*: Mathematical models and cube-type laboratory experiments are used to investigate the blasting process. Attention is given to fracturing in the borehole proximity due to blast induced stress waves, as well as gas pressurisation mechanisms driving comparatively few fractures many borehole radii.

The thesis presents new results of theoretical investigations, numerical simulations and experimental model tests, which lead to an improved understanding and perspective of the complex phenomena of rock dynamics in terms of stress wave and fracture propagation. The ultimate implications of this work are improved safety and efficacy of geotechnical operations, such as, for example, deep-level mining.

1 INTRODUCTION

Rock dynamics deals with transient processes such as stress wave and fracture propagation, and the interactions thereof, and the stability and integrity of rock loaded dynamically. Within the mining context, research in this field has been spurred in the last three decades particularly by the technical difficulties of deep-level mining operations and the associated occurrence of seismicity and rockbursts. Although the research effort has accelerated over the past decade, these dynamic events continue to account for the largest single cause contributing towards the toll of injuries and fatalities suffered by the workforce during mining operations.

The aim of this thesis is to conduct new and practically relevant work to gain further knowledge of rock dynamics. The work addresses stress wave propagation and the interaction with discontinuities, as well as dynamic fracturing due to stress wave loading and blasting.

More specifically, the main objectives can be classified according to the following categories, which are illustrated for a deep-level mining application in Figure 1 a); a photograph of a typical stope in a deep-level gold mine is given in Figure 1 b).

- **Stress Wave Interactions with Rock Mass Discontinuities:** Various types of rock joints and fractures, and the associated interface conditions, are analysed and their stress wave reflection and transmission characteristics are quantified.

- **Stress Wave Interactions with Tabular Mining Excavations:** The transient wave field due to wave interactions with mine excavations is investigated, and the mechanisms of energy channeling and fracturing due to the superposition of reflected, refracted and diffracted waves are studied.

- **Blasting:** The process of rock blasting is examined, where consideration is given to (i) blast induced stress waves and their proclivity for promoting fracturing in the borehole vicinity, and (ii) fractures driven by combustion gases.

The results reported in this thesis are based on analytical and numerical, as well as experimental investigations. A recurring theme throughout this work is the verification of numerical and analytical results by means of controlled laboratory experiments. This is considered an important aspect of the investigation and ensures accurate, relevant and meaningful results.

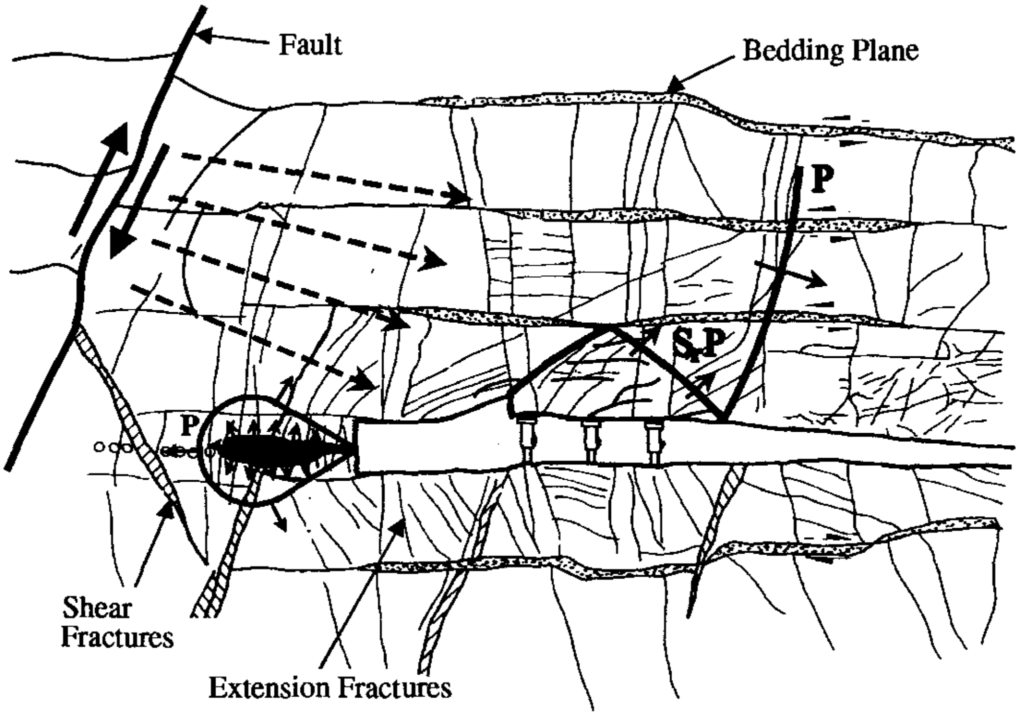


Figure 1 a): Stress wave propagation and dynamic fracturing in a deep-level mining operation.

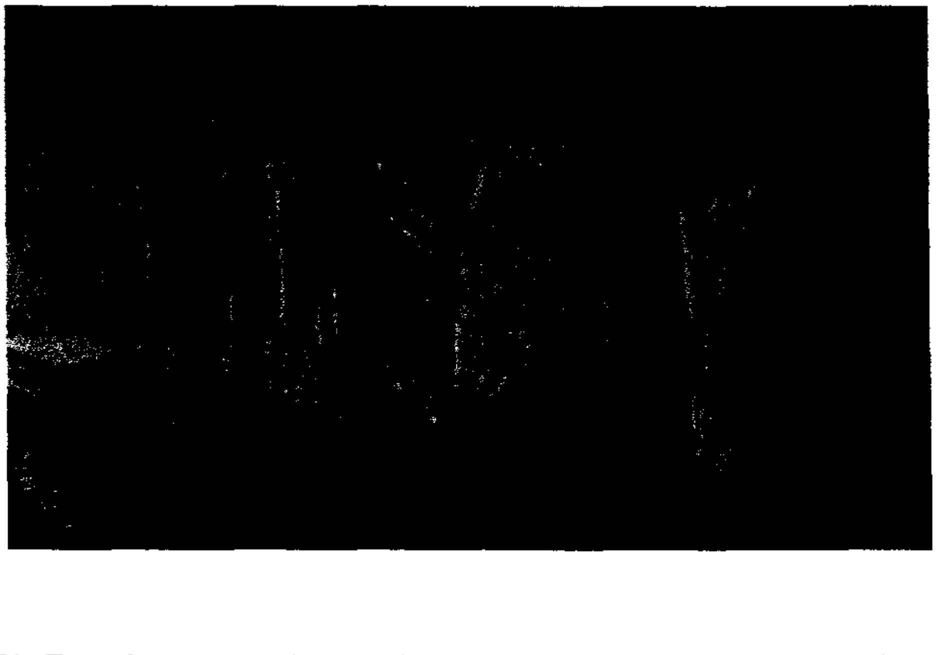


Figure 1 b): Typical stope in a deep level-gold mine showing support elements in the form of hydraulic props. These props are capable of controlled yielding in order to absorb energy as stress waves interact with the stope (courtesy of COMRO).

2 STRUCTURE OF THE THESIS

The thesis has six chapters. Each chapter is self-contained and the reader is introduced to the general subject at the beginning of the chapter. Each section within the chapter ends with a brief summary. A complete list of references is given at the end of the chapter. The titles and outline of each chapter are as follows:

- CHAPTER I – INTRODUCTION: The actuality of rock dynamics, the objectives and general methodology of research, and the thesis structure are addressed here.
- CHAPTER II – THEORETICAL CONCEPTS: The overall aim of this chapter is to review and develop the theory applied subsequently to model wave interactions with mining related discontinuities and the mechanisms associated with blasting. The first section in this chapter briefly reviews the elastodynamic theory used in the present study to describe wave propagation and interactions with discontinuities.

  In Section 2 the theory is applied to investigate in detail the interactions of stress waves with rock joints modelling various interface types. In addition to covering the well-known wave interactions with standard discontinuities, such as the free boundary and welded interface, some new interface conditions are analysed, e.g. interfaces with friction and shear strength, interfaces with normal and shear stiffness related to measurable rock joint properties, undulating rock joints and fluid filled interfaces.

  Section 3 gives a brief qualitative description of wave scattering by open slots; a basic understanding of these wave fields is required in Chapter IV to study the transient stress field generated during the interaction of waves with mining excavations.

  Finally, in Section 4, a literature review of dynamic fracturing is given. This overview is considered necessary to assess the capability of analytical fracturing models, the development and current state of the art of numerical models, and historical as well as topical experimental techniques which are suitable to investigate mechanisms governing dynamic fracturing.
- CHAPTER III – EXPERIMENTAL METHODS: Here, an overview of optical techniques (Section 1) and high speed photography (Section 2) is given. These experimental methods have proven to be suitable to investigate dynamic phenomena, and are subsequently applied in this study to gain new insight into mechanisms governing rock dynamics.
- CHAPTER IV – WAVE INTERACTIONS WITH MINING EXCAVATIONS: This chapter reports results of experimental and numerical investigations dealing with stress wave interactions with mining excavations. The experimental observations are back analysed by means of numerical

simulations, which are further applied to investigate energy channeling, stress intensification and fracturing.

In Section 1 of this chapter the elastodynamic behaviour is addressed, where emphasis is placed on the characteristics of the transient stress field resulting from wave reflection, refraction and diffraction.

Dynamic fracturing in the stope vicinity due to wave superposition is considered in Section 2. Numerical simulations are conducted to investigate the influence of various parameters on stress wave induced dynamic fracture propagation.

- CHAPTER V – BLAST INDUCED FRACTURING: The emphasis here is to analyse the nature of blast induced stress waves which lead to fracturing in the borehole vicinity, and gas driven fracturing. For this purpose a number of analytical, numerical and experimental studies are conducted and blasting mechanism are further quantified.

  An overview of the most important past and current developments dealing with fundamental blasting mechanisms is given in Section 1 of this chapter. In Section 2 the laboratory blasting results, which were conducted during the course of this research, are discussed. These experiments provide valuable data and qualitative insights of the evolution of fracture networks and gas pressurisation of propagating fractures.

  Section 3 gives characteristics of stress waves emanating from spherical, cylindrical and progressively detonating column charges, where in the latter case particular attention is paid to the effect of the velocity of detonation of the explosive.

  Gas driven fracturing is dealt with in Section 4 and important conclusions are formulated regarding the extent of gas driven fractures and the effect of various length-controlling parameters.

- CHAPTER VI – PRINCIPAL FINDINGS AND CONCLUSIONS: Finally, Chapter VI presents a brief overview of the work reported here and gives a summary of the new knowledge and advance in the state of the art of rock dynamics.

- APPENDIX: A single appendix supplies a list of publications in which parts of the thesis work are reported.

A brief overview of the findings of the main research topics and the advance in the state of the art is given in this thesis summary. The three principal research topics are identified as follows and are dealt with separately:

- **Wave interactions with rock joints** (Thesis Chapter II, Section 2),
- **Wave interactions with mining excavations** (Thesis Chapter IV, Sections 3 and 4), and
- **Blast induced fracturing** (Thesis Chapter V, Sections 2, 3 and 4).

3 WAVE INTERACTIONS WITH ROCK JOINTS

3.1 Introduction

Stress waves interacting with stopes are significantly influenced by pre-existing discontinuities such as bedding planes and rock joints surrounding the mining excavation. The aim of the work is to advance the understanding of stress wave interactions with pre-existing discontinuities, and to quantify amplitudes of waves born during the interaction process with various interface types.

Upon stress wave interaction with discontinuities, incident energy is reflected and refracted (transmitted). The resulting reflected and refracted waves affect the dynamic behaviour of the rock mass and can lead to dynamic stress concentrations, energy channeling and stress wave superposition, which can cause the rock to fracture and/or lead to loss of rock mass stability. Hence, in order to gain insights into the mechanisms associated with dynamic processes, such as blasting, percussion drilling and seismicity, knowledge of the amplitudes of the reflected and refracted waves is of importance.

A comprehensive study was conducted to determine the stress, energy, displacement and velocity amplitudes of stress waves reflected and refracted by a variety of interface types.

3.2 Previous Work

A large amount of literature deals with the subject of wave reflection and transmission across discontinuities. However, no single publication gives amplitude coefficients (i.e. the amplitude ratios of the reflected or refracted waves versus the incident waves) for a wide variety of interface conditions. Furthermore, a disadvantageous situation prevails as different authors give reflection and transmission coefficients for different physical quantities. The coefficients may be defined for potentials, displacement, velocity, stress and energy. Some authors (Graff, 1975; Kolsky, 1963; Miklowitz, 1978) give only amplitude coefficients of the potential functions, a quantity, which is difficult to interpret physically, whilst other texts give stress (Rinehart, 1975), energy (Miklowitz, 1978), displacement (Achenbach, 1973) or velocity (Rinehart, 1975) coefficients.

In practical work stress, energy and displacement coefficients are of use, depending on the specific application, purpose and discipline (e.g. blasting, seismology, percussion drilling, etc).

3.3 Objectives

The objective of this work is to supply a detailed and comprehensive set of curves giving stress, energy and displacement coefficients for reflected and refracted waves due to the interaction of incident *P*-, *SV*- and *SH*-waves with a range of interface conditions. In addition to covering the well-known wave interactions with standard discontinuities, such as the free boundary and welded interface, some new interface conditions are analysed, e.g. interfaces with friction and shear strength, interfaces with normal and shear stiffness related to measurable rock properties, undulating and dissipative joints. The work acts as a reference for the rock engineer, seismologist, geophysicist and blasting engineer, and assists in further understanding stress wave interactions with rock mass discontinuities.

Full details of the amplitude coefficients, as well as mathematical derivations and example problems illustrating the applicability of the coefficients to actual wave propagation problems, are published in the following:

Daehnke, A. and Rossmanith, H.P. (1997). Reflection and transmission of plane stress waves at interfaces modelling various rock joints. *Int. J. for Blasting and Fragmentation*, 1(2), (in Press).

Daehnke, A. and Rossmanith, H.P. (1997). Reflection and refraction of planes stress waves at dissipative interfaces. *Proc. of the 1st Int. Symp. on Damage and Failure of Interfaces*, ed. H.P. Rossmanith, Balkema, Rotterdam, (in Press).

Daehnke, A. (1997). SIMRAC Report: Stress Wave and Fracture Propagation in Rock. December, 1997.

Daehnke, A. (1997). Stress Wave and Fracture in Rock. Ph.D. Thesis, Vienna University of Technology.

3.4 Research Methodology

Reflection and refraction coefficients (ratio of the reflected/refracted wave amplitude versus the incident amplitude) are determined analytically by using the local (at the interface) stress, velocity and displacement components of the incident, reflected and refracted waves to satisfy the boundary conditions at the discontinuity (Figure 2). Stress, energy and displacement (= velocity) coefficients are calculated for incident *P*-, *SV*- and *SH*-waves at angles of incidence ranging from 0° to 90°.

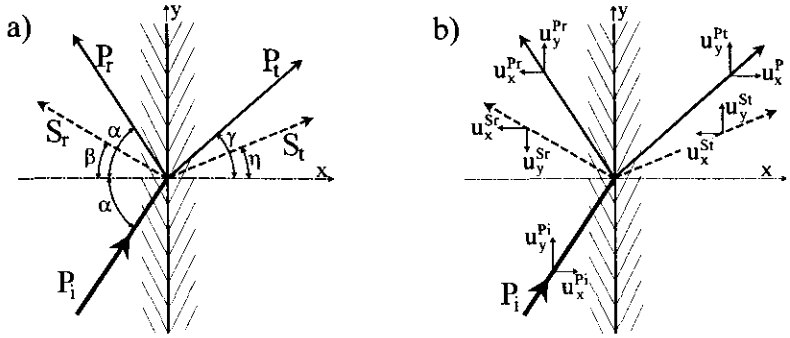
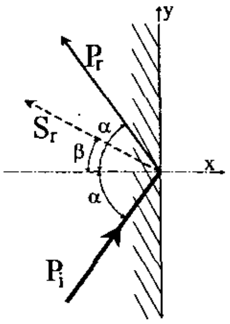


Figure 2: Displacement components of incident, reflected and refracted waves at a discontinuity.

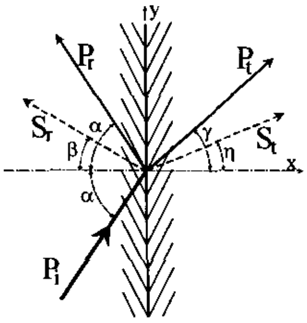
3.5 Discontinuity Types Analysed and Principal Results

A list of discontinuity types analysed follows below. Also included is a brief review of the findings of the new interface types investigated.

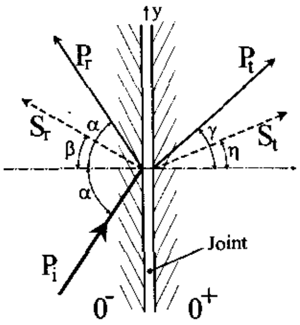
1. Free Boundary



2. Perfectly Bonded Interface

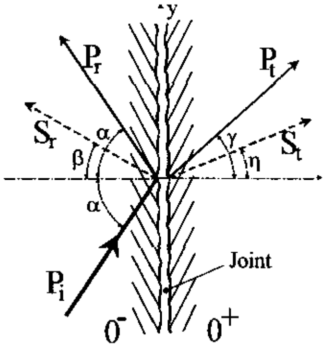


3. Non-Cohesive Frictionless Interface



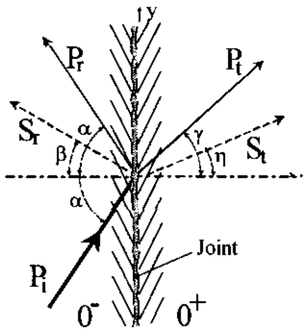
4. Non-Cohesive Frictional Interface

In the case of a frictional interface the amplitudes of the reflected and transmitted waves depend on the angle of wave incidence, Poisson's ratio, the acoustic impedance mismatch ratio and the coefficient of friction between the joint surfaces. During the slip process energy is dissipated; curves detailing the maximum energy dissipation versus angle of wave incidence and coefficient of friction are given.

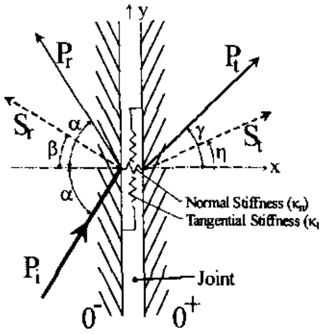


5. Cohesive Frictional Interface

Rock joints can contain narrow bands of filler material, which lend the joint normal and shear strength. Curves are given of the joint failure envelope (i.e. transition from intact to broken joint) versus internal friction, cohesive strength and angle of incidence for incident *P*- and *S*-waves.



6. *Interface with Equal Normal and Shear Stiffness*



Joints displaying normal and shear stiffness can be modelled by interface conditions relating the normal and tangential displacement to the normal and shear stresses acting at the joint surfaces, respectively. It is shown that the amplitudes of the reflected and transmitted waves depend on the frequency of the incident wave. Low frequency waves are more readily transmitted, whereas a higher portion of the energy of high frequency waves is reflected.

7. *Interface with Stiffness Values Related to Actual Joint Properties*

Empirical data is used to relate the normal and tangential joint stiffness to measurable rock properties. The joint stiffness can then be expressed as a function of the normal stress acting on the rock joint (e.g. see Figure 3). The amplitudes of reflected and transmitted waves are given for joint examples in dolerite, limestone and sandstone, and it is shown (for these joint types) that at a frequency of $f = 100$ Hz most of the incident energy is transmitted. At $f = 2000$ Hz the amplitudes of the waves reflected by the joint are approximately the same as the amplitudes of waves reflected by a free boundary, i.e. the transmitted energy is negligible compared with the reflected energy.

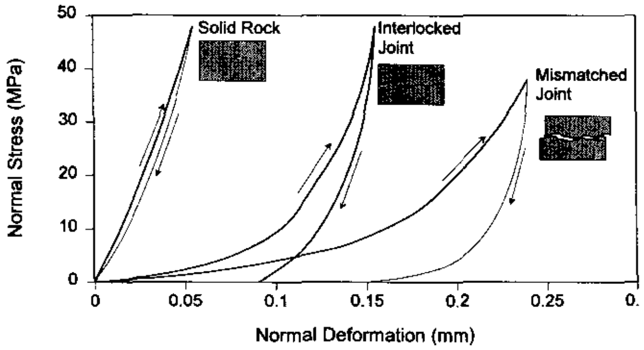
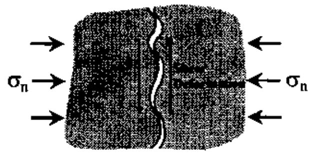


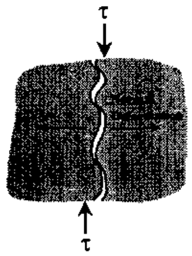
Figure 3: Normal stress versus deformation of various interface types.

8. *Pre-Stressed Joints*

It is shown that the reflection and transmission characteristics of rock joints are significantly influenced by the degree of joint pre-stress. Even at comparatively low pre-existing compressive stresses, significantly more energy is transmitted compared with unloaded joints. The implications of joint pre-stress are important in deep-level mining and for numerical modelling of stress wave propagation through fractured rock mass.

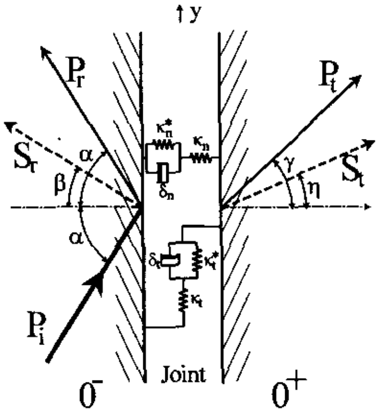
9. Undulating Joints





Interlocked, smoothly undulating joints can be modelled by cross-coupling the terms in the stiffness matrix. Generally, the stress amplitude of the reflected waves increases with increasing cross-coupling, whilst the amplitudes of the transmitted waves are reduced. A further unique effect of the cross-coupling is the generation of mode converted reflected and transmitted waves at normal wave incidence.

10. Dissipative Joints



The generalised Kelvin model is suitable to investigate the dynamic behaviour of interfaces modelling fluid filled joints, as well as discontinuities containing comparatively soft material. The reflection and transmission characteristics of this model are dependent on the joint stiffness, viscosity and the frequency of the incident wave. With increasing stiffness and viscosity, the amplitude of the reflected waves decreases, while more energy is transmitted. Increasing wave frequency results in more energy being reflected, and a reduced portion is transmitted.

For the Kelvin model analysed here, a maximum of 25 % of the energy can be dissipated during wave passage across the interface. It is shown that the energy dissipation is relatively insensitive to the angle of wave incidence. Values of wave frequency, joint stiffness and damping are given at which maximum dissipation occurs. Knowledge of this parameter window (at which maximum energy is absorbed) is important to assess the interface integrity during passage of seismic and blast induced stress waves

3.6 Summary and Conclusions

In summary, the characteristics of reflected and transmitted waves born during the interaction of incident stress waves with rock mass discontinuities are governed by a large number of parameters. This work has been published in two papers and represents, to the author's knowledge, the most comprehensive analysis of reflection and transmission coefficients for a wide variety of joint configurations and material parameters.

The most important advances in the state of the art in wave interactions with discontinuities have been made in the following areas:

- In this work the joint stiffness model is further developed to incorporate non-linear normal and tangential interface stiffness, where the relations governing the stiffness are based on actual joint properties. For typical joints analysed here, stress waves with a frequency of ± 100 Hz are predominantly transmitted, whereas at a comparatively high frequency of ± 2000 Hz most of the incident energy is reflected.

  Previously, although reflection and transmission coefficients were available for constant stiffness interface models, the coefficients were not related to actual joint properties and no lower – higher end frequency limits were established.

  The method developed here can be used to establish the reflection – transmission characteristics for any joint type, provided the interface surface properties have been determined by means of field or laboratory testing.

- An essential aspect of studies dealing with joint – wave interactions is the influence of joint pre-stress. This effect has previously been neglected. Based on actual interface properties, it is shown in this work that at even comparatively low levels of pre-stress, the joint reflection and transmission characteristics are altered significantly. With increasing pre-stress more energy is transmitted across the joint, and the amplitude of reflected waves is reduced. These results have important implications in deep-level mining applications and numerical simulations of wave propagation through fractured rock.

- The generalised Kelvin model is used to investigate the dynamic behaviour of interfaces modelling fluid filled joints. The reflection and transmission as well as energy dissipation characteristics of this model are quantified, and are found to depend on the joint stiffness, viscosity and wave frequency.

- Further novel work dealing with joint – wave interactions examines energy dissipation at frictional joints, failure envelopes for joints with cohesive filler materials, undulating joints and the influence of wave amplitudes.

represent tabular mining excavations (stopes), which are prevalent in, for example, South African deep-level gold mines.

Three model geometries are investigated:

(i) a stope situated in a homogeneous medium,

(ii) a stope surrounded by fracture softened material, where the interface (representing a parting plane) between the softened and bulk material is bonded, and

(iii) a stope situated within a softened material, with a non-cohesive material interface.

Prominent waves resulting from the diffraction, refraction and reflection of incident waves, as well as dynamic stress intensification at the stope face, stope back area and along the hanging-wall skin are analysed.

An example of theoretical, experimental and numerical results is given in Figure 4. Here an incident *P*-wave interacts with a stope bounded by non-cohesive parting planes. Experimental observations and isochromatic contours calculated by WAVE are given at a time instant 94 μs after blast-source activation, and good agreement between the experimental and numerical results is evident. Prominent wave types are a strong shear wave reflected by the material interface ($S_r P$), the reflection of the transmitted *P*-wave at the stope ($S_{sr} P_t P$), and the high density of reflected waves within the hangingwall beam immediately above the stope. The energy channeling and superposition is a possible mechanism for violent ground motion in the stope vicinity leading to rockbursts and falls of ground.

4.5 Fracturing due to Wave Interactions with Stopes

In the previously section the photoelastic technique was used to investigate the interaction of an incident *P*-wave with a stope; the focus here was on the distribution of wave energy in the stope vicinity and identifying potentially hazardous zones subjected to high dynamic stresses.

In this section further experiments are conducted to investigate the interaction of an incident *S*-wave with a stope surrounded by six pre-existing cracks. In this series of experiments the dynamic stresses propagated by the stress waves are of sufficient magnitude to re-mobilise and propagate the pre-existing cracks, and the emphasis of the work is on identifying wave types and mechanisms leading to fracture initiation and propagation.

The finite-discrete element program ELFEN is used to back-analyse the photodynamic experiments. ELFEN uses finite elements until a critical state of stress is reached, after which the element separates into two or more discrete elements. Remeshing is performed when breakage occurs.

4.5.1 Photoelastic versus Numerical Results

Numerous photodynamic experiments were conducted, and the results of the following three experiments are reported and discussed in the thesis:

(i) Waves incident at 45° to a stope in a homogeneous medium,

(ii) Waves incident at 45° to a stope bounded by non-cohesive parting planes, and

(iii) Waves incident at 90° to a stope in a homogeneous medium.

As an example of the photodynamic and numerical data, Case (iii) – Waves incident at 90° to a stope in a homogeneous medium – is briefly reviewed.

The geometry of the model used to investigate waves propagating at 90° towards the stope is shown in Figure 5.

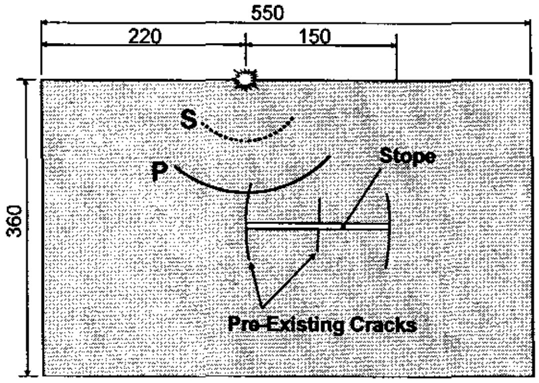


Figure 5: Model geometry used to investigate normal wave incidence (dimensions are in *mm*).

Figures 6 a) and b) show a stope surrounded by six near-vertical pre-existing cracks under loading of P- and S-waves propagating approximately normal to the stope. The photographs show the incident S-wave and the tensile $P_{sr}P$ wave due to the reflection of the compressive incident P-wave. Fractures initiate from the left-hand-side and middle cracks above the stope and propagate under strong mode I loading induced by the tensile $P_{sr}P$ and $S_{sr}S$ wave.

The photodynamic experiments were back-analysed by ELFEN and experimentally observed and numerically calculated fringe patterns and dynamically propagated fractures were found to correlate closely.

By back-analysing the laboratory experiments and finding good agreement between the numerical and experimental results, ELFEN has been verified to accurately model the mechanisms leading to fracture initiation and propagation.

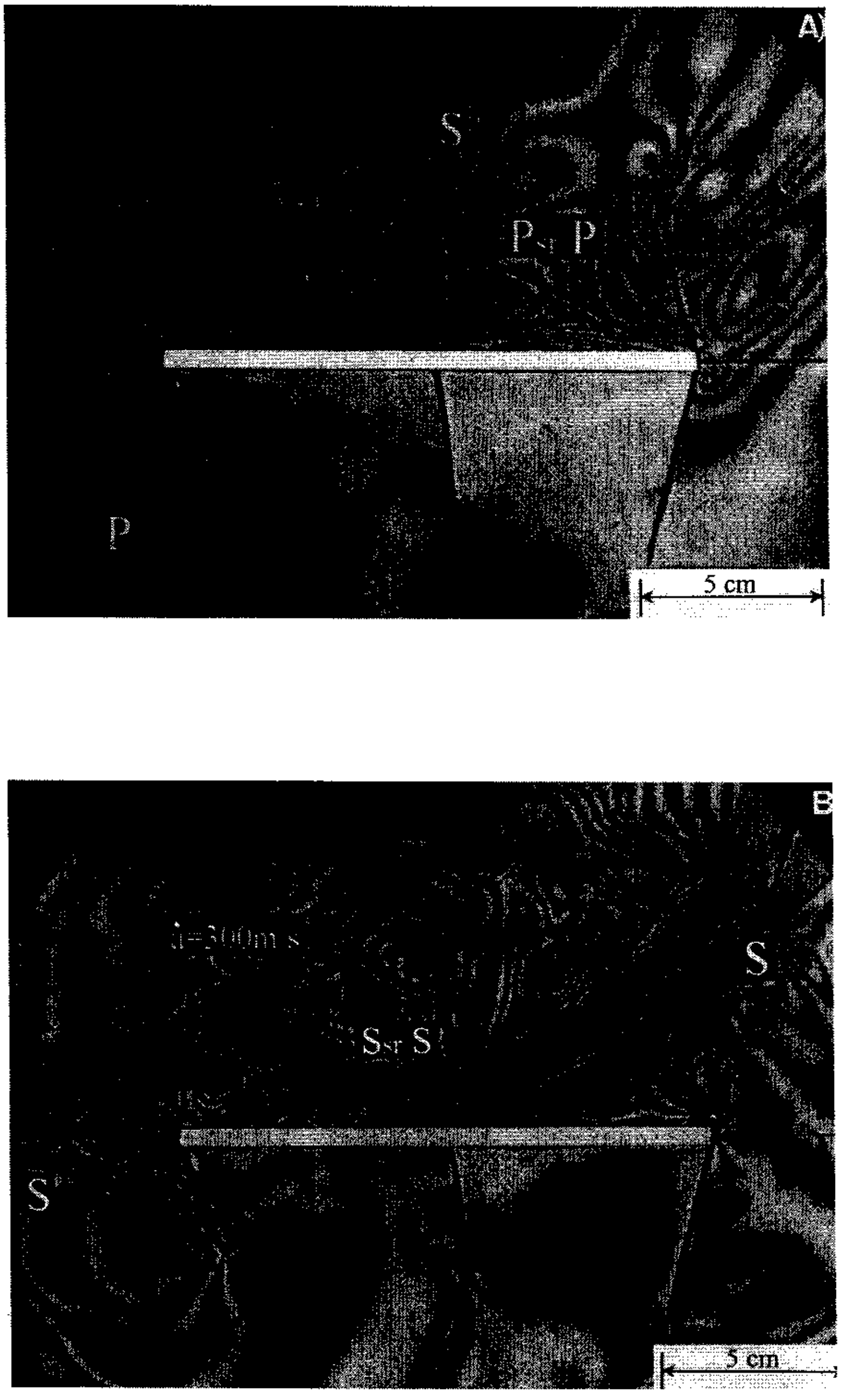


Figure 6 a) and b): Experimentally observed wave field 125 and 190 μs after charge detonation.

4.5.2 Mechanisms and Parameters Governing Dynamic Fracturing

ELFEN was used for a parametric study analysing dynamic fracturing due to the interaction of *P*- and *S*-waves with stopes. The investigation has illustrated various mechanisms leading to fracturing in the stope vicinity:

- In both cases of incident *P*- and *S*-waves, fracturing is primarily associated with the waves generated by reflection of the incident waves at the stope surface. An example of fracturing generated during the interaction of an incident *P*-wave is shown in Figure 7.
- Extensive stope parallel fracturing is observed at angles of incidence between 45° and 70°. The fracturing occurs due to $S_{sr}P$ and $S_{sr}S$ waves generated during the reflection of incident *P*- and *S*-waves, respectively.
- The shear wave polarity is shown to significantly influence the resulting fracture network, and a *S*-wave with wave front motion directed towards the stope induces more extensive fracturing than the case of a *S*-wave of opposite polarity.
- The stope support stiffness affects the extent of fracturing. Stiffer support (e.g. pillars) transmits more energy across the stope, and hence, compared with softer support, the amount of fracturing in the stope vicinity is reduced.

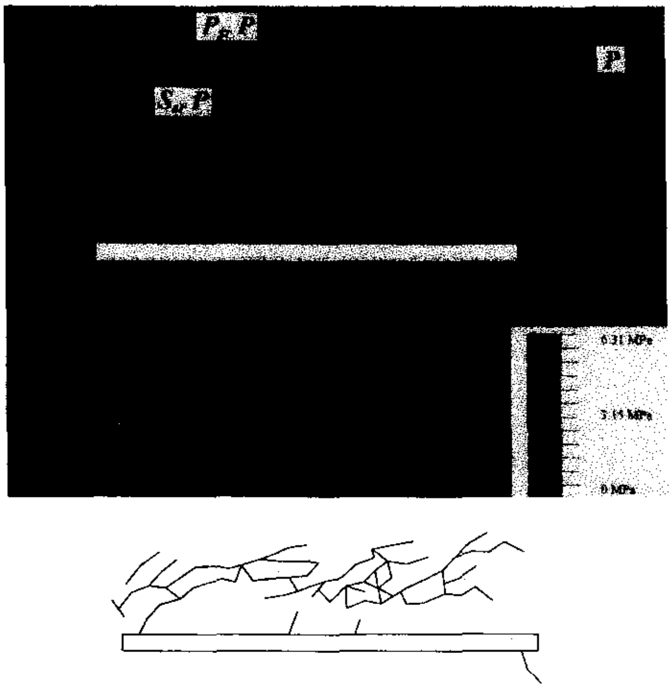


Figure 7: a) Isochromatic wave field due to a 45° incident *P*-wave interacting with a stope (top), and b) final dynamically propagated fracture network (bottom).

4.6 Summary and Conclusions

Seismic stress waves interacting with mining excavations are the most severe mining hazard associated with deep-level mines. The complicated radiation field resulting from stope – wave interaction leads to stress wave superposition, which can result in rock mass instabilities. Here, numerical and photoelastic investigations are used to identify zones of high dynamic stress concentrations and parameters influencing stress wave driven fracturing in the stope vicinity.

The main findings and advance in the state of the art are summarised as follows:

- Dynamic photoelasticity is used to visualise the complex stope – wave interactions and, by means of back-analyses, the numerical codes WAVE and ELFEN are verified to accurately model stress wave interactions and dynamic fracturing.

- This work has demonstrated that parting planes in general are found to reflect a portion of the incident energy and thus shield the stope. However, non-cohesive parting planes trap energy within the hanging-wall beam, and wave superposition associated with dense energy channeling gives rise to dynamic stress concentrations, which are likely to initiate fracturing and lead to rock mass instabilities.

- Numerical and experimental parametric studies are conducted to investigate stress wave driven fracturing in the stope vicinity. It is shown that fracturing occurs primarily due to reflected waves, and individual fractures are most likely to be oriented parallel to the free surface of the mining excavation.

  The polarity of incident shear waves significantly affects the extent of fracturing, and shear waves with wave front motion towards the excavation promote more extensive fracturing than incident *S*-waves with reversed polarity.

  Stiff stope support transmits a higher portion of energy across the stope; hence the amplitude of reflected waves is reduced, and less fracturing occurs. However, the required stiffness to substantially reduce fracturing is in the order of the rock mass stiffness (e.g. pillars), and support in the form of timber packs is comparatively too soft to significantly reduce fracturing.

5 BLAST INDUCED FRACTURING

5.1 Introduction

Knowledge of blast induced fractures is important to ensure efficient rock fragmentation and post-blast rock mass stability. Although drilling and blasting have been the principal methods of excavating hard rock for over a century, the fundamentals of the processes of explosive rock breaking have only been investigated comparatively recently. Most knowledge regarding blasting practices is based on field observations and empirical data, and relatively little is known about the fundamental mechanisms governing the interactions between the explosives and the rock mass, and ensuing fracture propagation.

5.2 Objectives

The aim of this investigation is to re-examine and gain new knowledge of the mechanisms leading to rock fragmentation by detonative media. These mechanisms are investigated by means of controlled laboratory experiments and mathematical modelling of the blast process. Particular attention is paid to the interaction between the detonating explosive and the rock, and the ensuing gas driven fracture propagation. The main findings of this work are reported according to (i) *Experimental Investigation*, (ii) *Borehole Breakdown and Stress Wave Propagation*, and (iii) *Gas Driven Fracturing.*

5.3 Experimental Investigation

Three dimensional cube-type laboratory models were fabricated from PMMA, and dynamically loaded with explosives. The dynamic evolution of the resulting spatial crack system was monitored by taking a sequence of high speed recordings with a Cranz-Schardin type camera. The laboratory models are designed to give insights into mechanisms creating damage and fracture zones in the immediate borehole vicinity, as well as gas pressurisation mechanisms which drive comparatively few radial fractures many borehole radii.

A total of 13 cube-type experiments were conducted and the noteworthy experiments discussed in the thesis are:

Penny Shaped Crack:

A novel experiment was designed to propagate a planar penny shaped crack. The purpose of the experiment is to investigate gas driven fracturing and the experimental data is subsequently back-analysed by an analytical/numerical model simulating dynamic fracturing due to gas pressurisation (Section 5.5). Photographs of the propagating penny shaped crack show a lag between the gas and crack front (Figure 8). This phenomenon has previously been theoretically predicted, however this is the first physical evidence of the vacuum behind the propagating crack tip.

Sealed Charge:

Upon detonation of a sealed short cylindrical charge, two prominent conical cracks propagate from the charge ends. Data from this experiment is subsequently used during numerical back-analyses in order to verify a computational technique to model gas driven conical cracks (Section 5.5). Practical applications of sealed explosives are, for example, the underground detonation of nuclear charges.

Stemmed Charge:

Detonation of a stemmed charge results in wedge or axi-radial shaped fractures propagating radially along the borehole length. A comparatively small conical crack extends from the blind end of the borehole. The stemmed borehole represents the most common charge configuration in mining operations and wedge or axi-radial fractures are the predominant fracture type occurring in praxis.

Stemmed Charge Intersecting a Plane of Weakness:

When a charge intersects a plane of weakness, interface delamination is likely. In the experiment conducted here the fracture direction was not influenced by the interface, however fractures did not propagate across the interface. Combustion gases pressurise the weak layer, which delaminated at approximately the same rate as the fracture propagation speed.

Stemmed Charge in an Uni-Axial Stress Field:

In underground mining, blast induced fracturing is influenced by the pre-existing stress field. Here it is shown that fractures originally propagating radially from the borehole are reoriented to subsequently propagate in the direction of the maximum principal stress.

Line Charge:

Two line charge experiments were conducted to investigate fracturing resulting from the progressive detonation of a column charge. Fractures are observed to extend radially and along the length of the borehole, and comparatively small conical fractures form at the borehole ends. Upon inspection of the stress wave driven fracturing in the immediate borehole vicinity, fracture kinking is apparent between 2 and 4 borehole radii. Mechanisms leading to the fracture kinking are accounted for by investigating the maximum tensile stresses of the transient stress field due to charge detonation (Section 5.4).

5.5 Gas Driven Fracturing

In the final section of this chapter gas driven fracturing is studied. A coupled solid, fluid and fracture mechanics numerical/analytical model is used to analyse gas driven fracture propagation. The model is novel in terms of incorporating dynamic material properties, quasi-dynamic fracture mechanics, as well as convectional and conduction heat transfer from hot combustion gases to the surrounding rock. The model is verified by back-analysing laboratory experiments, and good correlation between numerical and experimental data is observed. The analytical/numerical model, which can predict propagation rates and the final fracture extent, gives insights into gas pressure, temperature, density and velocity profiles within propagating fractures.

A method is proposed to estimate the final lengths of radial fractures for a given quantity of combustion gases, where the gas quantity is related to the explosive type and borehole diameter or charge mass. The method is applied in the form of a parametric study to investigate various parameters governing the extent of blast induced fractures in confined rock.

It is found that the final fracture extent is relatively insensitive to the initial borehole pressure, whereas fracture extent increases with higher initial gas temperatures. Increasing in-situ stress, rock fracture toughness, number of fractures and gas-leakoff due to seepage all reduce the final fracture extent. For the parameters investigated, the influence of in-situ stress has the greatest bearing on fracture extent, whilst in confined rock a wide range of fracture toughness values results in a comparatively minor variation in fracture extent.

Various thermodynamic models are discussed, and it is shown that approximate models (e.g. adiabatic and isothermal gas flow) over-emphasise fracture extent. To accurately model combustion gas induced fracturing, it is recommended to take conductive and convective heat transfer into account.

The analytical/numerical method is further developed to model gas driven conical cracks. By means of numerically determined correction factors for the crack opening displacements and stress intensity factors, the penny shaped crack is generalised to a 45-degree conical crack. The modified model is verified by back-analysing a laboratory experiment and good agreement between the numerical and experimental data is observed.

The extent of conical fractures propagating in a uniform compressive stress field in hard, competent rock is estimated, and it is shown that, with increasing compressive stresses, fracture growth is inhibited. By approximating a 45-degree conical crack with a penny shaped crack the fracture extent is underestimated, and it is recognised that the conical geometry has a significant influence on fracture growth. Gas driven conical cracks had not been analysed previously.

5.6 Summary and Conclusions

An important aspect of rock dynamics is blast induced fracturing. By means of laboratory experiments and mathematical modelling the blasting process is investigated. Specific attention is given to blast induced stress waves and gas pressurisation mechanisms driving comparatively few fractures many borehole radii.

A brief overview of the findings and advance in the state of the art of blasting science follow below:

- Novel three dimensional cube-type laboratory experiments were conducted in specimens fabricated from PMMA and dynamically loaded with explosives; the resulting stress wave and fracture evolution was recorded by means of high speed photography. The experiments give new insights into the evolution of fracture systems due to detonation of various charge geometries.

  Photographs of the lag between the gas and crack front are given. This lag has previously been predicted theoretically, however this is the first physical evidence of the vacuum behind the propagating crack tip.

- The transient stress field due to the progressive detonation of a column charge is quantitatively studied by means of numerical analyses. It is shown that the shape of the pressure profile acting on the borehole walls has a relatively small influence on the dynamic stress field.

  When the velocity of detonation of the explosive exceeds the shear wave speed of the material, it is found that the maximum tensile stress initially acts in a tangential direction. At a distance of 2 – 3 borehole radii the maximum tensile stress acts in an approximately axial direction, and fracture re-orientation is likely. This fracture kinking has been observed in laboratory blasting experiments. At a detonation velocity below the Rayleigh wave speed of the material, the borehole is effectively pressurised quasi-statically, and the dynamic stresses are low in magnitude.

- An advanced and improved combined analytical/numerical method is used to simulate gas driven fracturing. The method is verified by means of comparisons with data obtained using laboratory experiments. Previously, a similar analysis was checked by limited post-blast data, and in this investigation a detailed verification is possible by correlating data obtained during the complete gas driven fracturing process.

- A new method is proposed to estimate the gas driven fracture extent in competent rock compressed by a uniform stress field. The influence of gas pressure, temperature, in-situ stress, rock fracture toughness, number of fractures and gas leak-off due to seepage on the final fracture extent is illustrated. This is the first study to quantitatively assess the effect of these parameters on fracture extent related to explosive type and amount.

  Various thermodynamic models are assessed and the importance of incorporating heat transfer from the hot combustion gases to the surrounding rock is shown.

  The results given here have important practical implications for blasting in confined rock, well-bore stimulation and rock pre-conditioning as is currently practiced in some deep-level mines in South Africa, the USA and Canada.

- Gas driven conical cracks extend typically from sealed charges and borehole ends, and have not been investigated in detail previously. Here, the combined analytical/numerical method is further enhanced to model gas driven conical cracks. Practical results are given in the form of relating the final fracture extent of sealed charges, at various levels of in-situ stress, to the type and amount of explosives.

6 CLOSURE

The thesis presents new results of theoretical investigations, numerical simulations and experimental model tests, which lead to an improved understanding and perspective of the complex phenomena of rock dynamics. The results are particularly applicable to underground and open-cast mining operations.

An important aspect of the work is the verification of analytical and numerical results by means of laboratory experiments, thereby ensuring accurate as well as relevant and meaningful results.

The implications of this work are improved safety and efficacy of geotechnical operations.