CHAPTER 1

EVALUATION OF STOPE SUPPORT USING A ROCKMASS STIFFNESS APPROACH

1.1 INTRODUCTION

As early as in 1556 Georgius Agricola described in his book De Re Metallica the total mining process from the exploration phase to the extractive metallurgical processes for different minerals, as it is known today. He describes in much detail each step and process from the exploration, the functions of each of the Officers from the Mining Prefect that is appointed by the King, the Bergmeister that oversees the mining practices and who reported to the Mining Prefect, the Mine Manager, the Foreman (Shiftboss as we know it today) as well as that of the Miner, including all the services that are related to the above including that of the Surveyor and the Clerk of the Bergmeister.

Agricola identified certain geotechnical environments but did not have the means or the technical knowledge that we have today to address the problems he encountered. He refers to the geotechnical properties of the rockmass as being "crumbling", "hard", "harder" and "hardest." He also stated: "Since the whole mountain, or more especially the whole hill, is undermined, it is necessary to leave the natural pillars and arches, or the place is timbered". This will be described as pillars i.e. regional support in today's terminology.

He further went on to say: "But sometimes when a vein is very hard it is broken by the fire, whereby it happens that the soft pillars break up, or the timbers are burnt away, and the mountain by its great weight sinks into itself, and then the shaft buildings are swallowed up in the great subsidence. Therefore it is advisable to sink some shafts which are not subject to this kind of ruin, through which the materials that are excavated may be carried out, not only while the pillars and underpinning still remain whole and solid, but also after the supports have been destroyed by fire and have fallen". We would refer to this as mining layout and having a second outlet.

In the latter part of the book he simplistically states that the rockmass in a shaft or tunnel that is "crumbling" to "hard" requires "more timbering" than the other and that in some instances the "harder" and "hardest" rocks do not require any support at all. It is evident that timber played a major part in the mining process since it was advisable that a mine be situated where trees and water were readily available. The timber was required for support of the shafts and tunnels while the water was essential for the washing process during the extraction of the minerals from the ore.

Interesting to note is the fact that there were even then the critics that claimed: "..... mining is a perilous occupation to pursue, because the miners are sometimes killed by pestilential air which they breathe; sometimes their lungs rot away; sometimes the men perish by crushed in masses of rock; sometimes, falling from the ladders into the shafts, they break their arms, legs, or necks; and it is added that there is no compensation which should be thought great enough to equalise the extreme dangers to safety and life". He went on to say that: "These occurrences, I confess, are of exceeding gravity, and moreover, fraught with terror and peril, so that I should consider that the metals should not be dug up at all, if such things were to happen very frequently to the miners, or if they could not safely guard against such risks by any means. Who would not prefer to live rather than to possess all things even metals?"

Throughout the history of the mining industry the support of the underground excavations has remained one of the primary activities not only for the stability of the workings, but also ensure the safety of the workforce. The material used for the support of these excavations has to be in available in sufficient quantity and in close proximity to the mine while at the same time cost effective. Timber was used as support from the days of Agricola and even today still forms the major component of stope support in the South African gold and platinum mines.

Timber has also been used for the support of stopes and auxiliary excavations since the discovery of gold on the Witwatersrand. At present a variety of timber and concrete packs and props are still in use in both shallow and deep mines.

Stope support design is one of the more complex design issues in the field of mining engineering. The objective of stope support has never changed from the early days of shallow gold mining on the Witwatersrand until now. The aim has always been to ensure the stability of the underground excavation and in so doing create a stable, safe and production friendly working environment for the underground workforce.

Stope support is to be designed in a way that it meets the requirements of different conditions underground. The selection of stope support type in the early days was based on mining experience as well as knowledge and interpretation of local underground rock conditions. The support materials used were those that were readily available in volume in relatively close proximity to the mining operation at reasonable cost.

In those early days the miners practised some of the important concepts that are generally accepted in stope support design methodology today. Miners were for instance aware of the need for pre-stressing of stope support during installation, and one development that satisfied this need was the development of the so-called "Q-block." Limitations of ordinary timber props or sticks were also realised early on. According to Jeppe (1946) attempts to overcome the lack of yieldability in a stick was achieved by sharpening one end of the stick to induce yield at a lower load. Jeppe also reported favourably on a compressible pipe support filled with sand.

No evidence could be found in literature that a rigorous engineering approach was adopted in the design of stope support during the early days of gold mining in the Witwatersrand.

Stope support is designed for the following areas of interest:

- Face area;
- Working area;
- Back area; and
- Remote back area.

The definitions of those areas are described in the Glossary of Terms, Chapter 9.

According to the information obtained from the Department of Minerals and Energy (2002) the current rock production from the gold and platinum mining industries in South Africa is some 180 million tons per annum. It is predominantly produced from stopes that require support of some type. This production relates to an annual expenditure of just over R1 Billion per annum (Kruger, 2002) for the support of these on-reef excavations.

It is believed that the work described in this thesis will contribute towards a safe and production friendly production environment. Much progress has been made over the past number of years in reducing the rockfall accidents for all mining sectors, as illustrated in Figure 1.1. The fatalities that are related to seismicity show an increasing trend for the same period. The 2002 data is a projection from January to May for the same year. It is for this reason that the mining industry will continuously strive to improve safety and it is believed that this thesis may contribute towards a better understanding of the rockmass-support interaction.

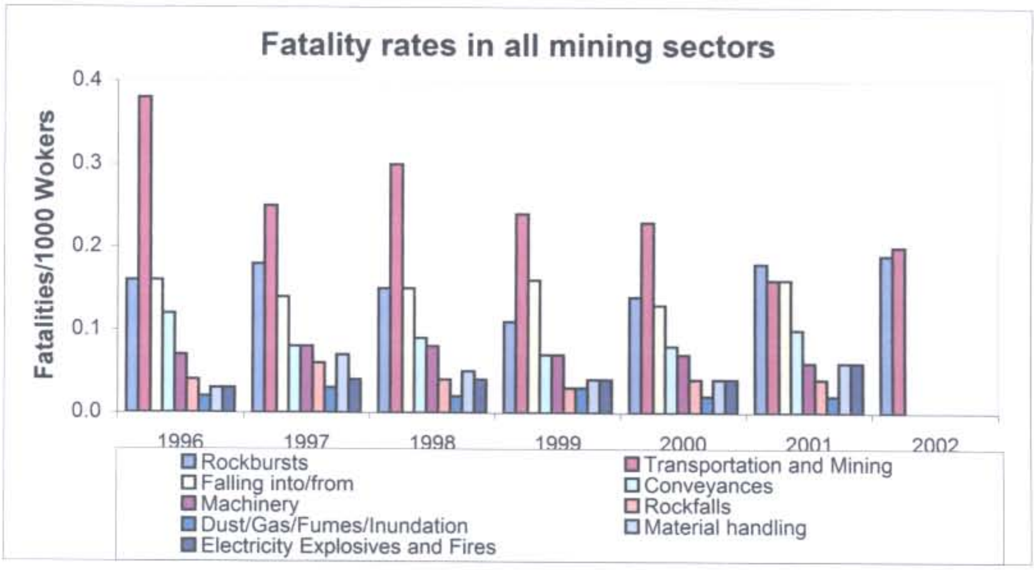

Figure 1.1: Fatality rates for different categories for all mining sectors from 1996 to 2002

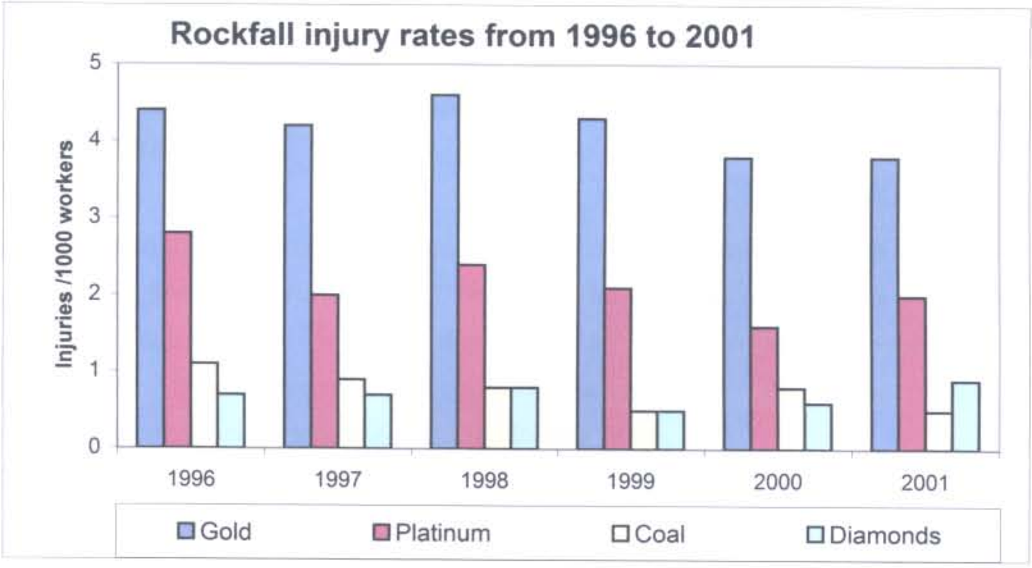

Figure 1.2: Rockfall injury rates for the four largest mining commodity sectors for 1996 to 2001

The majority of the rockfall accidents occur in the gold and platinum mining sectors, as shown in Figure 1.2.

The stope face is the focus for the design of support that is described in this thesis. Figures 1.3(a) and 1.3(b) confirms that the majority of the accidents occur on the stope face. This research may contribute to improve on the safety through a proper understanding of the ability of the support to react to the support demand required from the rockmass.

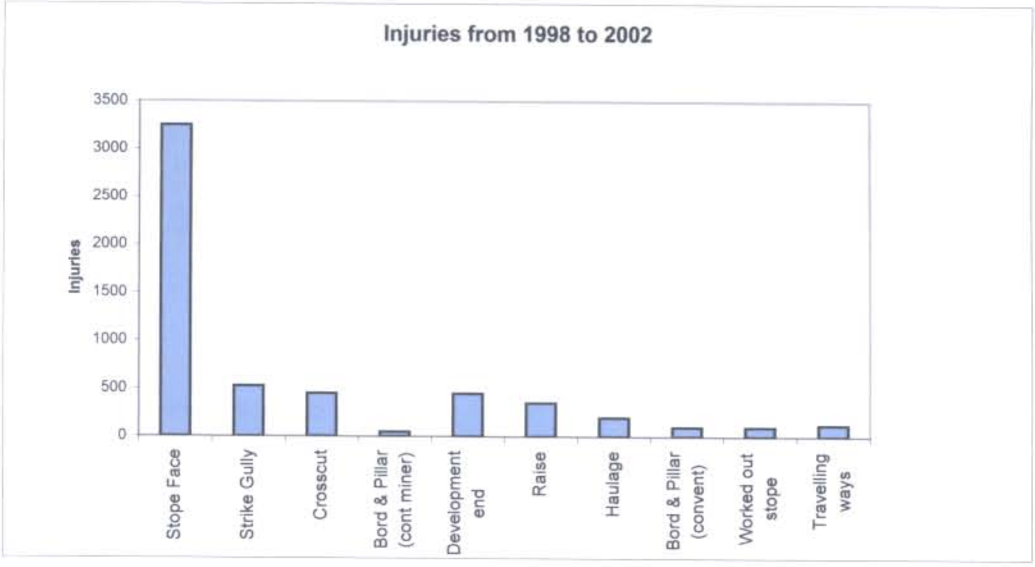

Figure 1.3(a): Rock related (including rockfall and rockburst) injuries by working place from 1998 to 2002

The primary function of support installed in a stope is to maintain the continuity and integrity of the fractured hangingwall beam in the stoping area. This is achieved by applying a sufficient force to the immediate hangingwall so as to generate frictional forces between individual segments of the hangingwall beam. The support must be able to perform this while experiencing varying closure rates.

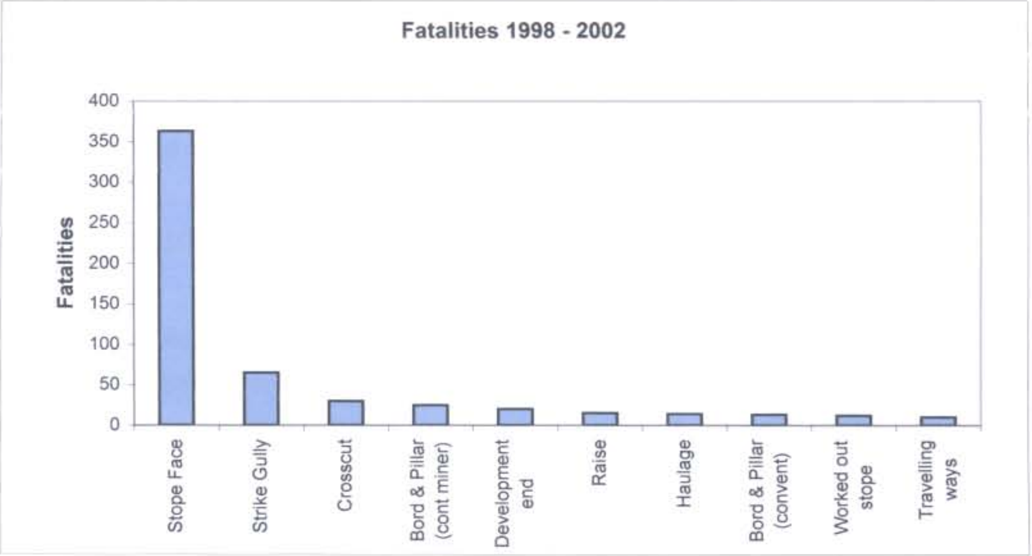

Figure 1.3(b): Rock related (including rockfall and rockburst) fatalities by the working place from 1998 to 2002

Support in the mining industry is divided into a number of categories. The support types used in the mining industry can be categorised according to:

Function of support

- Temporary support;
- Permanent support;

Characteristics of support

- Stiff support;
- Soft support;
- Active support;
- Passive support;

Position of support

- Face support;
- Regional support;

Description of support

- Tendon support;
- Elongate type of support;
- Props;
- Sticks;
- Timber packs;

- Cementitious packs; and
- Reef pillars.

These are listed and defined in the Glossary of Terms, Chapter 9.

1.2 CONTRIBUTION OF THIS RESEARCH

The stability analysis described in the thesis investigates the stability of the stope as this impacts on both the safety of the workforce and the stability of the stope as the single most important excavation.

The research includes most of the support types used in the South African mining industry today and investigates and evaluates stope support for the stope as a district. It includes the face area, working area, back area and remote back area.

The support that is investigated for the purpose of stability analysis at any one time depends on the loading, which is determined by the so-called attributed area that is considered by this design process.

The attributed area as described in Chapter 5 is determined in a manner that the influence of stope abutments and regional support is taken into account. All support types that are installed in these areas are taken into consideration as well as the factors influencing their performance. The in-situ performance or capacity of stope support is used in the analysis process. This is compared to the demand placed on the support from the model describing rockmass behaviour.

The following is a summary of issues described by the research to address some of the current shortcomings of stope support design in the field of rock engineering:

- The methodologies described in the thesis take into consideration the support demand from the rockmass, considering rockmass behaviour, as well as the performance or capacity that the stope support units can offer. Both are considered as variables according to the position relative to the stope face and other abutments and the state of deformation of the support. Factors influencing both of these are described mathematically and incorporated into the final model where the impact of these on excavation stability is evaluated. The outcome of the analysis are expressed and compared on a common x-y axis.

- The approach is a novel one describing rockmass behaviour in terms of the stiffness of the surrounding rockmass in comparison to the stiffness of the support element at different stages of deformation.

- Strain softening of a support unit forms an integral component of the design. This characteristic of stope support has been neglected in the past during the design process. No evidence could be found in literature where strain softening is determined and its effect on excavation stability analysed. The important role of this phenomenon in the design and analysis of support is illustrated in the thesis.

- The model that is developed takes into account the varying performance characteristics of a support unit(s) during the process of its deformation. It includes aspects such as load generated by the support unit, varying stiffness and energy absorption capacity. Esterhuizen (1996) developed a three-dimensional design methodology that is available to the rock engineer as a design tool is one of the models. This model only takes into account the presence and position of support units in relation to the stope face.

- As far as could be established in literature, this is a first where the performance characteristics of support elements are described and presented in a mathematical format. This provides a tool in the hand of the rock engineer that could be viewed as similar to a seismic waveform that is described through a Fourier transformation. By manipulation of the mathematical equation is it possible to generate the source parameters and characteristics of that particular event. The approach described in the thesis makes it possible that the support performance function is manipulated mathematically to compensate for factors that influence its performance and present the real or in-situ performance of the unit.

- The methodology takes face shape and presence and position of regional support into consideration. The support design methodology that is proposed is simple to use and does not require time-consuming numerical computer modelling. It would be attractive as a design tool to rock engineering practitioners in general.

- The mathematical equations that have been developed can be used with current pseudo three-dimensional numerical design programs such as Minsim W in order to compare various support types. In-situ support resistance generated by a support system that is installed at any given spacing can be calculated and contoured in this way. This is achieved by dividing the support performance function by the tributary area supported by each support unit. It takes face shape and presence and position of regional support into consideration.

1.3 ROCKMASS BEHAVIOUR

A substantial amount of research has been done in the mining industry with the objective to describe and predict rockmass behaviour. It seems unfortunate that this work has never been incorporated into a three dimensional design procedure that could be used by rock engineering practitioners for stope support design. Brummer (1985) described the behaviour of the immediate hangingwall of a stope by dividing the hangingwall into triangular blocks or wedges. Even though this work generated valuable insight into the behaviour and failure of the stope hangingwall, the analysis is restricted to two dimensions.

Backfill is probably one of the fields most thoroughly researched in terms of support and its interaction with the stope hangingwall. Although the majority of these papers do not explicitly describe hangingwall behaviour, Goldbach (1991) has done valuable research in quantifying ground motion by analysing the effect of backfill on the rockmass in comparison to conventional (unfilled) supported stopes. The results from this study together with work on ground motion analysis in backfilled stopes, show how backfill can reduce the overall ground motion during seismic events. The in-situ modulus of the rockmass has also been determined by Gürtunca and Adams (1991) through the use of backfill instrumentation.

The research described in the thesis is an attempt to describe rockmass behaviour by quantifying the rockmass stiffness at a given point in space and in time for a given mining geometry and layout. The strata stiffness can be calculated for different mining stages and geometry with varying rates of closure and different support types at any point of interest. The analysis can include both areas with and without regional support. The interaction of the stope support and the rockmass for a number of case studies is evaluated and the outcome of the stability analysis compared to underground observations.

1.3.1 The concept of rockmass stiffness

This research is aimed at developing a better understanding and description of the interaction that exists between the rockmass and stope support. This is investigated from an original and novel approach utilising the concept of rockmass stiffness and is an innovative approach applied in the scope of stope support evaluation.

The concept of rockmass stiffness forms the basis for the design methodology described in the thesis. In literature only some reference is made to the concept of strata stiffness with regard to rockmass behaviour. Ozbay and Roberts (1988) discussed pillar failure and referred to "possible load lines" during an analysis of yield pillars in stopes. No definite or fixed values for the stiffness of the load lines is quoted, but the comment made that the more pillars there are, the stiffer the strata. This statement is confirmed in this research, where values for the stiffness of strata are quoted.

Ryder and Ozbay (1990) focus on a methodology for the analysis and design of a pillar-mining layout. It was stated that the strata stiffness is nominally a property of the strata alone, and is in fact directly proportional to the Young's modulus of the strata. They confirm and also suggested that strata stiffness is a very complex concept. This research shows that the strata stiffness underground is strongly influenced by the geometry of mining and in particular by the number and position of regional support pillars. Ryder and Ozbay (1990) accepted the latter but no further comments were made, or values for the stiffness of the strata quoted in their work. They accepted that as the number of pillars subject to collapse increases, so the governing critical strata stiffness tends to decrease; generating conditions less and less favourable for stability. In the limit, for a very large mined out area featuring no regional support, the strata stiffness approaches zero; thus implying regional collapse if the pillars are overloaded and exhibit any post-failure negative slope. This statement that was made by these two authors is confirmed by this research.

The stope hangingwall is not taken as an elastic homogeneous rockmass with a linear rate of deformation from the stope face towards the back area as is the case with the stope and gully support design. In this research the actual closure is taken at a point of interest during different intervals of mining and the strata stiffness calculated for each mining step. The geometry of the underground layout is also taken into account during the analysis as well as the position and presence of regional support. This is seen as a very important aspect in the design of stope support and believed to be a limitation of the other design methodologies. It is believed to be unique to the work described in the thesis and this methodology may therefore be classed as fully three-dimensional.

1.4 EXCAVATION STABILITY

The stability of the underground excavation is of utmost importance not only for the safety of the workforce and protection of equipment, but also to ensure a continuous and uninterrupted production cycle. The interaction of the support and the rockmass is not unique to this study and has been studied by a number of authors.

One of the more prominent of these previous studies is the rock-support interaction for tunnels that is described by Hoek and Brown (1980) and Brady and Brown (1985). The interaction between the support and the rockmass for a *tunnel* is represented by means of the *required support lines* for the excavation walls and the support reaction or *available support* lines and presented on a common support pressure-tunnel deformation axes as illustrated in Figure 1.4.

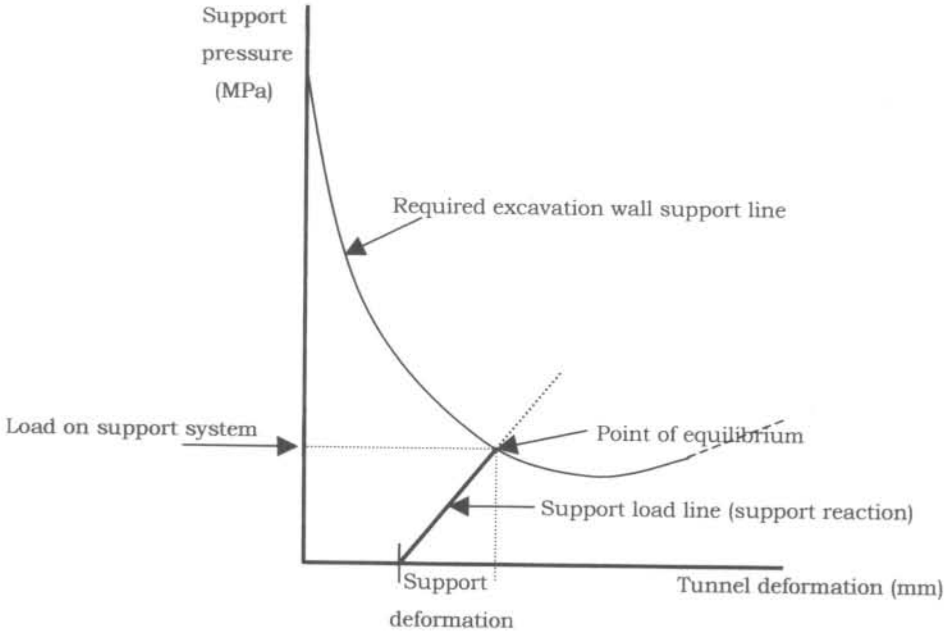

Figure 1.4: Principles of rock-support interaction for a tunnel, after Hoek and Brown (1980)

The support for a tunnel typically loads along a path such as shown in Figure 1.4 and is known as the support reaction or available support line. The curve representing the behaviour of the rockwalls is known as the ground characteristic or required support line. Equilibrium between the rock and the support is reached at the point of equilibrium as illustrated. The major role of the support and reinforcement is thus to control the rock displacements. The stiffness of the support element, its strength and the time of installation of the support have an important influence on this displacement control, and hence the stability of the tunnel.

The concept of evaluating support based on the interaction of support units and the rockmass, is not new. However, the concepts have not yet been applied to tabular stope excavations and the various parameters have not been quantified in real situations.

In the study described in this thesis, the rockmass is not approached as a homogeneous, isotropic and elastic medium as assumed in elastic numerical modelling, but fails in a number of different ways. The prediction and description of rockmass failure is complex and difficult to describe and quantify. To ensure the stability of the underground excavation and improve the safety of the workforce is it essential that the in-situ performance of different support elements in different localities relative to the stope face be predicted for the accurate design of a support system. It is of paramount importance that the mode of failure of each of these elements be properly understood and addressed.

Stope support units have a finite strength depending on its dimensions and the type of material from which the unit is constructed. Support will yield and fail in different ways during the process of deformation. The support-rockmass interaction that is presented in the thesis focuses on the rockmass load line that describes the way in which the support is loaded by the rockmass during successive stages of mining. The reaction of the support is described and the mode of failure is determined. This failure can take place in either a controlled- or uncontrolled fashion.

1.5 SUPPORT CHARACTERISTICS – SUPPORT CAPACITY

1.5.1 Review of database

The Support Catalogue that was published as part of the SIMRAC GAP032 research project by CSIR Mining Technology (1995) was used as database from which the base support curves of the different elements were extracted. These were then adjusted to reflect in situ behaviour. The laboratory load-deformation test curves were used showing the load generated by the support element in kilonewton versus deformation in millimetres. The support type, height of support unit tested and the test rate of deformation (mm/minute) are also published in the database.

This Support Catalogue is widely used as database for support test curves in the mining industry. Curves of the more popular support types used in mining industry and in particular the ones for the areas of interest for the research were utilised. Some of the packs that are described were however developed subsequent to the publication of the Support Catalogue. Laboratory test results in such cases were obtained from the manufacturer.

The characteristics of the various support elements are described by studying their load-deformation curves. From these curves the initial stiffness, load bearing capacity whilst deformation takes place, post failure stiffness and energy absorption ability of the support can be determined and compared to other support units. These characteristics are summarised and defined as the support *capacity* of a support unit.

The database used in the thesis includes a variety of timber- and timber composite packs, lightweight cementitious packs, timber elongates and sticks with varying base dimensions, diameters and heights.

This information becomes of particular interest when adjustments are made to the laboratory performance of the support elements to quantify the in-situ behaviour of such an element. This process is described in detail in Chapter 4.

1.5.2 Mathematical representation of support performance

The curves in the Support Catalogue produced by the CSIR Division of Mining Technology as part of the GAP032 SIMRAC research project are used to describe the behaviour of stope support mathematically. Polynomials of the n^{th} order are fitted to the curves of the most popular support elements used in the mining industry at the time. Pretorius (1995) showed that the force generated by a support element could be expressed as a function of its deformation by a mathematical equation. This approach makes it possible that the equation be manipulated mathematically to compensate and quantify the influence that different parameters have on support performance.

A load at deformation intervals of 5 millimetres or less was taken so that an accurate representation of the laboratory result could be produced mathematically. This was repeated for all the support elements of interest and the data tabled in load-deformation (x-y) co-ordinates. The support curve is reproduced mathematically by fitting an n^{th} order polynomial to the x-y co-ordinates. In most cases a sixth order polynomial produced the most accurate representation of the laboratory curve. These functions are described in Chapter 4.

The factors that influence the performance of a support element were also described in a mathematical format. These factors are the pre-stress force during installation, rate of deformation, creep, influence of the height of pack installed as opposed to the one tested and buckling potential in the case of a timber elongate type of support. This mathematical function is combined with the original support function into what is referred to as the combined or adjusted mathematical function for support. The adjusted functions are all described in Chapter 4.

1.6 SUPPORT PERFORMANCE FEATURES

The performance characteristics that are calculated for a support element represents the in-situ performance of each unit taking into consideration the factors that influence its performance. The function is manipulated mathematically so that the following performance features can be determined through the analysis:

1.6.1 In-situ load generated by the support element; (kN)
1.6.2 Support resistance generated by the support element; (kN/m^2)
1.6.3 Stiffness of support (both strain hardening and softening); (kN/mm)

1.6.4 Energy absorbed by the support element for a given deformation interval; (kJ) and
1.6.5 Stress exerted onto rockwalls during quasi-static or dynamic loading. (MPa)

1.7 DESIGN METHODOLOGY

Design methodologies that are commonly practised in the mining industry are the following:

1.7.1 Established usage

This is done by establishing what type(s) of support is successfully used elsewhere in the industry under conditions similar to the one being investigated. For this method to be successful is it important that the underground conditions be comparable and that ground conditions be of similar geotechnical classification. This method is commonly practised in the South African mining industry.

1.7.2 Trial and error

This is one of the more popular methodologies used in the South African mining industry for many years. The fact that stope support is such a complex design issue makes this a very attractive option. With this methodology different support elements are put on trial and their performance monitored carefully. Alterations and modifications are made to the support system on a continuous basis when and if required. This could in a way be compared to the New Austrian Tunnel Method (NATM) where support is adjusted after certain underground conditions are observed.

1.7.3 Empirical observation

In this case the rock engineer relies on what he can observe and measure from experiments and underground trials rather than design strictly according to a stope support design theory or prescribed methodology. This methodology is practised quite often especially with the design and development of new types of support. The underground support spacing is altered on an ongoing basis until such time that the rock engineering practitioner is confident that the support satisfies set criteria that are often not quantified but based on underground observation and experience. The spacing of the support elements is often determined and influenced by practical considerations such as the lower limit for strike support spacing in breast mining that is often dictated by the width of the face scraper.

1.7.4 Comparative experimental simulation

Testing of support elements is nothing new, and not unique to the mining industry of today but was done by Bowden in the early 1900's. Extensive load-compression tests have been done on all types of packs including concrete reinforced packs. He highlighted for instance the effect of timber density on pack performance. This led to the conclusion then that timber support elements could be constructed in a way that it is as effective as any other of the support combinations tested.

The fact was even then identified that the support characteristics determined from laboratory tests are different to the underground performance of that same unit. Research at the time by Riemann (1986) indicated that the load bearing ability of timber supports from conventional laboratory tests does not provide reliable information for predicting underground performance.

Roberts, Jager and Riemann (1987) and Taggart (1996) have done valuable work since then to quantify the effect that loading rate has on the performance of both timber packs and timber elongates. The relevant adjustment factors were determined and described. These factors have been included in the thesis while the remainder were developed and mathematical models drawn up to describe the effect that it has on the performance of support elements such as cementitious and composite types of support.

Probabilistic keyblock analyses by Daehnke et al (1998) have shown that, for a typical discontinuity spacing and attitude as encountered in intermediate- and deep-level gold mines, the support spacing in the dip direction can be increased by a factor of approximately 1.5 of the strike spacing, while maintaining an equal probability of keyblock failure in the dip versus the strike direction. It is therefore recommended in general that the support spacing in the dip direction should not exceed 1.5 times the spacing in the strike direction.

1.8 OBJECTIVE OF THESIS

In spite of the many advances that have been made in the fields of numerical modelling and rock mechanics the behaviour of the hangingwall of a stope is still not fully understood. Several anomalies exist between the observed behaviour of the rock in the immediate hangingwall of a stope, and the predictions of the various modelling techniques currently available to the industry.

It is essential that the behaviour of the hangingwall, and in particular the interaction between the hangingwall rockmass and the support system be better understood to effectively design stope support.

A study of the behaviour of a rockmass and expressing that in terms of exact scientific values is almost impossible. No firm scientific figures can be quoted for any rockmass and exact rockmass behaviour predicted from that. A rockmass will not repeatedly react in exactly the same manner under similar conditions.

The different approaches taken by researchers and engineers to produce an "all-inclusive" model for stope support design reflect the complexity of this topic. The current study on stope support design was initiated during years of careful observation of different stope support types and its reaction during various stages of mining at varying depths for both quasi-static and dynamic loading conditions.

The thesis is an attempt at developing an engineering design approach for stope support that will address at least some of the limitations of other methods. It is done with the aim to describe both the capacity of a support system and compare that to the demand placed on a support system by the underground excavation it is intended to support.

Much emphasis is placed on the interaction that exists between stope support and its immediate hangingwall, introducing concepts of support– and rockmass stiffness and energy absorption capacity. Both the behaviour of stope support and that of the surrounding rockmass are analysed for different mining geometries at varying stages of mining.

The author believes that the research done and presented in the thesis can quantify and reproduce to some extent aspects of the behaviour of stope support observed underground. Limitations perceived to exist in the mining industry and particularly with regard to the design of stope support are addressed. It is believed that this work will contribute towards a better understanding, analysis and design of stope support in the discipline of rock engineering.

The last phase of the thesis contains descriptions that will enable the design engineer to perform his/her own evaluations by varying some or all of the parameters like:

- The geometry of the underground excavation;
- Point of interest within the underground excavation;
- Presence and position of regional support;
- Stope width;
- Rate of closure;
- Support spacing; and
- Hangingwall beam thickness.

The influence that the above have on the stability of the excavation is determined qualitatively.

One of the major contributions of this research towards the discipline of rock engineering design is the ability to represent both rockmass demand and support capacity on common axes and test for stability by varying parameters that are common and influence both.

1.9 SCOPE OF STUDY

1.9.1 Support model

The main objective of the thesis can be summarised as developing a stope support design and analysis methodology. The study comprises three phases of models to compare the demand imposed on stope support by the rockmass to the capacity of the support.

A stope support model is developed to describe the behaviour or performance of stope support mathematically. A number of factors influence the performance of stope support elements. These factors are also described in a mathematical format to compensate for it.

This process makes it possible that adjustments can be made to the original mathematical model describing the support element to compensate for any of the influences. The final combined mathematical equation gives a representation of the in-situ performance of the support element under discussion.

1.9.2 Rockmass model

The aim of the second model, that is the rockmass demand model, is to describe rockmass behaviour in a way that it can be linked directly to the stope support model.

The manner in which this is achieved is by the utilisation of the concept of strata stiffness. The local strata stiffness for any point in the underground environment is calculated using the force component from the attributed area and the closure component from underground measurements at that point.

The slope of the force-deformation line represents the strata stiffness. This is determined for the different stages of mining represented by a change in the excavation geometry.

Magnitudes for deformation (that is the x-axis) are obtained from underground instrumentation where stope closure is measured at certain intervals for the point(s) of interest. These values are therefore model independent.

The value for force (on the y-axis) is determined originally through the application of yield lines as described by Johansen (1962). This principle was developed further during the study to what is referred to as the attributed area concept. Through this analysis an area gets attributed to a point of interest at an underground measuring station for a given stope geometry and closure. A representative force is calculated from the attributed area at any point for a given mining stage.

1.9.3 Combined model

The two models, these are for stope support and rockmass behaviour, are combined into a single model during the third stage of the study. During this stage the capacity of the support is compared to the demand imposed on it by the rockmass. The data is represented on a common x-y axis.

Factors influencing any one or both models can be varied and the effect that it may potentially have on the stability of the excavation is quantified.

1.10 LAYOUT OF THE THESIS

The study described in the thesis is done in three phases. A mathematical model describes each of these phases. The first phase consists of a model that represents the capacity of stope support where laboratory test results of different support elements are described mathematically.

The factors that influence the performance characteristics or capacity of the support elements are also described mathematically and combined with laboratory tests into a single function that represents the in-situ performance of a particular support element. **This procedure is described in detail in Chapter 4.**

The behaviour of the rockmass is described during the second phase of the research introducing the concept of strata stiffness. The concept of yield lines as described by Johansen (1962) were introduced and developed further to what is referred to as the attributed area concept. From the analysis the strata stiffness is determined during different stages of mining taking cognisance of the mining geometry and presence of regional support. **This is described in Chapter 5.**

These two stages are combined into a single mathematical representation of the rockmass demand versus support capacity. This constitutes the third phase of the study. The combined representation takes into account all aspects influencing demand of the rockmass as well as those influencing support performance.

In **Chapter 6** the rockmass demand is compared to the support capacity through manipulation of the models by varying the influences that are related to both. These are typically aspects such as rate of closure (quasi static to dynamic), underground geometry, face shape, presence and position of regional support, type and spacing of stope support, thickness of immediate hangingwall beam, stoping width, height of test pack and rate of deformation during laboratory test.

The outcomes of these analyses are used to establish and quantify the effect that this variable would have on the stability of the underground excavation. In **Chapter 7** the stability is evaluated and assessed in case studies by comparing the stiffness of the stope support to that of the rockmass. The energy absorption capacity of the support in relation to that generated by the rockmass is also evaluated. The capacity of the support system as a whole is compared to the demand placed on it by the rockmass this way.

In isolated cases some of the diagrams are repeated. This is done with the objective to make easier reading of the document.

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