



UNIVERSITEIT VAN PRETORIA  
UNIVERSITY OF PRETORIA  
YUNIBESITHI YA PRETORIA

# **EVALUATION AND DESIGN OF OPTIMUM SUPPORT SYSTEMS IN SOUTH AFRICAN COLLIERIES USING THE PROBABILISTIC DESIGN APPROACH**

İsmet Canbulat

Submitted in partial fulfilment of the requirements for the degree Philosophiae Doctor in the  
Faculty of Engineering, Built Environment and Information Technology, University of Pretoria,

Pretoria, 2008



## Abstract

### Evaluation and Design of Optimum Support Systems in South African Collieries Using the Probabilistic Design Approach

by

İsmet Canbulat

**Supervisor** : Professor J.N. van der Merwe

**Co-supervisor** : Professor M.F. Handley

**Department** : Mining Engineering

**Name of degree** : Philosophiae Doctor

**Keywords:** Coal mine, roof support design, probabilistic design, roof stability, roof failure

This thesis addresses the problem of designing roof support systems in coal mines. When designing the roof support, it is necessary to account for the uncertainties that are inherently exist within the rock mass and support elements. The performance of a support system is affected by these uncertainties, which are not taken into account in the current design methodologies used in South Africa. This study sets out to develop a method which takes all uncertainties into account and quantitatively provides a risk-based design.

Despite the fact that the roof bolting is probably one of the most researched aspects of coal mine ground control, falls of ground still remain the single major cause of fatalities and injuries in South African collieries. Mainly five different support design methodologies have been used; namely, analytical modelling, numerical modelling, physical modelling, design based on geotechnical rating systems and field testing. As part of this study, it is shown that there are many elements of a support system that can impact the support and roof behaviour in a coal mine and the characteristics of these elements as well as the interaction between them is complex and can vary significantly within a short distance. These variations account for uncertainties in coal mine roof support and they are usually not taken into account in the above design methodologies resulting in falls of ground and/or over design of support systems.

The roof and support behaviour were monitored at 29 sites at five collieries. It is found that there was no evidence of a dramatic increase in the stable elevations as experienced in some overseas collieries. A roadway widening experiment was carried out to establish the critical roof displacements. The maximum width attained was 12 m at which stage 5 mm displacement was measured. During the monitoring period no roof falls occurred at any of the 29 sites and road



widening experiment site, even where 12 mm displacements were measured. The in situ monitoring programme was continued in additional 26 monitoring stations in 13 sites with the aim of establishing the effect of unsupported cut-out distance on roof and support performances. The results showed that the lithological composition of the roof strata plays a major role in the amount of deflection that was recorded. Bedding separation was seen to occur at the contacts between different strata types. It is concluded that the roof behaved like a set of composite beams with different characteristics. It is also found that the amounts of deflection corresponded with the deflection that would be expected from gravity loaded beams. During this monitoring programme variable nature of roof and support systems are also demonstrated.

As many mines use different geotechnical rating systems, an evaluation of the currently used classification techniques were conducted to determine their effectiveness in design of roof support strategies. It is found that currently used systems cannot quantitatively determine the required support system in a given geotechnical environment. Impact splitting tests are found to be the appropriate system for South African conditions. It is however concluded that the roof lithology, stress regime and roof characteristics can change within meters in a production section. Therefore, in order to predict these changing conditions many boreholes are required for a section, which would be costly and time consuming.

An in-depth study into the roof support elements was conducted for the purpose of obtaining an understanding of the fundamental mechanisms of roof support systems and developing guidelines for their improvement. All of the currently available roof bolt support elements and related machinery were evaluated using *in situ* short encapsulated pull tests. The results showed that, on average, bond strengths obtained from the roof bolts supplied by different manufacturers can vary as much as 28 per cent. The test results conducted on different resins showed that the strength of resin currently being used in South Africa is adequate. Differences between commonly used bit types were established. It is concluded that the 2-prong bit outperforms the spade bit in sandstone and shale rock types. In addition, the effect of hole annulus was also investigated as part of this study. The results show that an annulus between 2.5 mm to 3.8 mm resulted in the most effective bond strengths. The effect of wet and dry drilling was noted. It is found that bond strengths and overall support stiffnesses are greater with the use of the wet drilling in all resin types. The results from the tests in different rock types highlighted the very distinct differences between bolt system performances. Quality control procedures for compliance with the design, support elements and quality of installation are presented. Recommendations for improving the quality control measures and for developing testing procedures for bolt system components, installation quality and resin performance are provided.



Finally, a roof support design methodology that takes into account all natural variations exist within the rock mass and the mining process has been developed and presented. This was achieved by adapting a probabilistic design approach using the well established stochastic modelling technique. This methodology enables rock engineers to design roof support systems with greater confidence and should result in safer and economic extraction of coal reserves.



## Acknowledgement

I would like to gratefully acknowledge that the research described in this thesis was made possible by funding provided by Safety in Mines Research Advisory Committee (SIMRAC) of the Department of Minerals and Energy of South Africa.

I would like to thank my research supervisor, Prof. J.N. van der Merwe of University of Pretoria, for giving me this great opportunity to work on this thesis and for his invaluable contribution, encouragement and his friendship. Without him this thesis could never have been put together.

The Division of Natural Resources and the Environment of the CSIR is acknowledged for their support.

Dr. Güner Gürtunca and Dr. Francois Malan are thanked for their personal support and encouragement.

Mr. Phil Piper of Groundwork Consulting (Pty) Ltd is thanked for his guidance.

The project team; Dr. Bernard Madden, Gary Prohaska, Bruce Jack, Adam Wilkinson and Thandile Dlokweni are thanked for assisting me in underground investigations and in the analyses of the data and also for their friendship and great support.

Tony Jager and Dr John Ryder for reviewing this thesis, and for their invaluable suggestions and recommendations throughout the thesis.

South African coal mines and Rock Engineers, D. Minney, L. Munsamy, G Makusha, J.J. van Wijk, J. Latilla, E. Wevell, D. Neal, D. Postma, B. Vorster and many others of Anglo Coal, BHP Billiton (Ingwe), Xstrata Coal and Sasol Coal are thanked for their support and assistance.

Most of all to my wife, Şemsa, I thank you for your patience and encouragement. Without your support I would have never made it to the end. All my love and wish to my son, Ali Tolga. I would also like to express my sincere gratitude and deep respect to my father Servet, my mother Fikret, and my brothers, Necdet and Vedat.

Thank you all.



## Table of Contents

	<i>Page</i>
<b>Abstract</b> .....	<b>ii</b>
<b>Acknowledgement</b> .....	<b>v</b>
<b>Table of Contents</b> .....	<b>vi</b>
<b>List of Figures</b> .....	<b>x</b>
<b>List of Tables</b> .....	<b>xvi</b>
<b>Glossary</b> .....	<b>xviii</b>
<b>Chapter 1.0 Introduction</b> .....	<b>1</b>
1.1 Background.....	1
1.2 Objectives and scope of research.....	3
1.3 Outline of the thesis .....	4
<b>Chapter 2.0 Literature review</b> .....	<b>6</b>
2.1 Introduction .....	6
2.2 Types of roof bolts .....	6
2.2.1 Mechanical coupled roof bolts .....	8
2.2.2 Resin point anchors .....	11
2.2.3 Full-column single-resin-type bolts .....	13
2.2.4 Full-column slow/fast-resin combination bolts .....	15
2.2.5 Friction rock stabilisers .....	16
2.2.6 Wooden dowels and fibreglass dowels.....	17
2.2.7 Spin-to-stall system.....	18
2.2.8 Current guidelines for the selection of roof bolt type.....	19
2.3 Theories of roof bolting support .....	23
2.3.1 Simple skin support.....	24
2.3.2 Suspension mechanism.....	25
2.3.3 Beam-building mechanism.....	26
2.3.4 Keying.....	27
2.4 Roof bolting design .....	28
2.4.1 Analytical methods.....	28
2.4.2 Field testing.....	30
2.4.3 Numerical modelling .....	37
2.4.4 Roof support design based on geotechnical classification .....	39
2.4.5 Physical modelling .....	39
2.4.6 Probabilistic methods.....	41
2.5 Geometric parameters .....	42
2.5.1 Bolt length.....	42
2.5.2 Bolt diameter.....	44
2.5.3 Bolt pattern.....	46
2.5.4 Annulus size.....	46



2.6	Tensioned versus non-tensioned bolts .....	47
2.7	Stiffness of roof support .....	49
2.8	Intersection support .....	50
2.9	Discussion and conclusions .....	51
<b>Chapter 3.0 Underground monitoring of roof and support behaviour .....</b>		<b>54</b>
3.1	Introduction .....	54
3.2	Underground monitoring procedure .....	54
3.3	Processing of information .....	56
3.4	Colliery 'A' .....	60
3.4.1	Site performance summary Colliery 'A' .....	61
3.5	Colliery 'B' .....	65
3.5.1	Site performance summary Colliery 'B' .....	74
3.6	Colliery 'C' .....	76
3.6.1	Site performance summary Colliery 'C' .....	77
3.7	Colliery 'D' .....	83
3.7.1	Site performance summary Colliery 'D' area 1 .....	104
3.7.2	Site performance summary Colliery 'D' area 2 .....	104
3.7.3	Site performance summary Colliery 'D' area 3 .....	105
3.8	Colliery 'E' .....	105
3.9	Analysis of underground field measurements .....	112
3.9.1	Time effects of a static face on bord stability .....	114
3.9.2	Migration mechanism .....	114
3.10	Roadway widening .....	118
3.10.1	Instrumentation .....	119
3.10.2	Widening procedure .....	121
3.10.3	Results .....	123
3.10.4	Conclusions .....	127
3.11	Conclusions .....	130
<b>Chapter 4.0 Effect of cut-out distance on roof performance .....</b>		<b>132</b>
4.1	Introduction .....	132
4.2	Research conducted .....	132
4.2.1	Summary of current knowledge .....	136
4.3	Underground monitoring .....	137
4.3.1	Introduction .....	137
4.3.2	Underground monitoring procedure .....	138
4.3.3	Processing of information .....	143
4.4	Colliery 'A' .....	143
4.4.1	Colliery 'A' Site 1, Test 1 .....	144
4.4.2	Colliery 'A' Site 1, Test 2 .....	145
4.4.3	Colliery 'A' Site 2 .....	146
4.4.4	Colliery 'A' Site 3 .....	147
4.5	Colliery 'B' .....	153
4.5.1	Colliery 'B' Site 1 .....	153
4.5.2	Colliery 'B' Site 2 .....	154



4.5.3	Colliery 'B' Site 3	155
4.6	Colliery 'C'	160
4.6.1	Colliery 'C' Site 1	160
4.6.2	Colliery 'C' Site 2	161
4.6.3	Colliery 'C' Site 3	162
4.7	Colliery 'D'	167
4.7.1	Colliery 'D' Site 1	167
4.8	Colliery 'E'	170
4.8.1	Colliery 'E' Site 1	170
4.9	Colliery 'F'	173
4.9.1	Colliery 'F' Site 1	173
4.10	Analysis of underground monitoring results	176
4.11	Investigation of trends using numerical modelling	184
4.12	Conclusions	189
<b>Chapter 5.0 Evaluation of geotechnical classification techniques to design coal mine roofs</b>		<b>193</b>
5.1	Introduction	193
5.2	Coal Mine Roof Rating (CMRR)	194
5.2.1	Evaluation of CMRR	199
5.3	Rating systems being used in South African collieries	201
5.3.1	Rating systems developed for planning purposes	201
5.3.2	Proactive rating systems developed to identify changing conditions	208
5.3.3	Colliery specific systems being used in South Africa	210
5.4	Geotechnical testing at different collieries	210
5.4.1	Colliery 'A'	211
5.4.2	Colliery 'B'	214
5.4.3	Colliery 'T'	219
5.4.4	Colliery 'K'	221
5.4.5	Colliery 'N'	223
5.4.6	Colliery 'S'	224
5.5	Application of proactive systems	225
5.6	Conclusions and recommendations	226
<b>Chapter 6.0 Evaluation of roof bolting systems in South Africa</b>		<b>228</b>
6.1	Introduction	228
6.2	Specifications for roofbolters	229
6.2.1	Introduction	229
6.2.2	Testing procedure	230
6.2.3	Results	232
6.2.4	Effect of wet and dry drilling	250
6.3	Performance of roof bolts	252
6.3.1	Performance of roof bolts manufactured in South Africa	252
6.3.2	Tensioned versus non-tensioned roof bolts	253
6.3.3	Variation in roof bolt parameters	255
6.4	Performance of resin	261
6.5	Specifications for bolt and resin	264





6.6	Effect of bit, annulus and rock type.....	268
6.6.1	Performance of bits.....	268
6.6.2	Effect of hole annulus .....	271
6.6.3	Effect of rock types .....	272
6.7	Quality control procedures for support elements .....	273
6.7.1	Support elements.....	275
6.7.2	Compliance with the design .....	283
6.7.3	Installation.....	283
6.8	Conclusions .....	284
<b>Chapter 7.0 Roof support design methodology.....</b>		<b>288</b>
7.1	Introduction .....	288
7.2	Support design based on a probabilistic approach .....	288
7.2.1	Rules of probability .....	289
7.2.2	Methodology of probabilistic approach .....	289
7.2.3	Required number of runs in Monte Carlo simulation.....	294
7.2.4	Acceptable probability of stability.....	295
7.3	Roof behaviour and failure mechanism .....	298
7.3.1	Failure and support mechanisms.....	303
7.4	Roof bolting mechanisms .....	304
7.4.1	Suspension mechanism.....	304
7.4.2	Beam building mechanism.....	305
7.5	Determination of stability of the immediate layer between the roof bolts .....	310
7.6	Probability density functions of design parameters and random selection.....	311
7.6.1	Goodness of fit tests .....	315
7.6.2	Probability distributions of design parameters .....	316
7.7	Support design methodology .....	317
7.8	Application of the probabilistic design approach to a case study.....	320
7.9	Conclusions .....	332
<b>Chapter 8.0 Conclusions and recommendations .....</b>		<b>334</b>
8.1	Conclusions .....	334
8.2	Recommendations for future research.....	347
<b>References .....</b>		<b>349</b>



## List of Figures

Figure 1-1	Fatality and injury rates in South African collieries for the period 1984 to 2001 .	2
Figure 1-2	Cause for fatalities in South African collieries for the period 1995 to 2001 .....	2
Figure 2-1	The length-capacity relationships that have evolved for roof bolts, cable bolts, and ground anchors (after Windsor and Thompson, 1997) .....	7
Figure 2-2	Mechanical anchor bolt .....	9
Figure 2-3	Forces acting on the components of an expansion shell anchor (after Windsor and Thompson, 1997).....	9
Figure 2-4	Various expansion shell mechanisms (after Windsor and Thompson, 1997) ...	11
Figure 2-5	Point resin anchor .....	12
Figure 2-6	Full column resin bolt .....	14
Figure 2-7	Full-column slow/fast-resin combination bolts (the dual resin system) .....	15
Figure 2-8	Split Set .....	17
Figure 2-9	Spin-to-stall installation procedure (after Minney and Munsamy, 1998) .....	19
Figure 2-10	Selection of bolt type (after Maleki, 1992).....	20
Figure 2-11	Simple skin support.....	25
Figure 2-12	Suspension mechanism .....	25
Figure 2-13	Beam-building mechanism.....	26
Figure 2-14	Keying effect of bolting.....	27
Figure 2-15	Compression zone created by keying (after Luo et al., 1998).....	27
Figure 2-16	Short encapsulated pull test equipment (after DMCIDC, 1996) .....	32
Figure 2-17	A typical short encapsulated pull test result.....	34
Figure 2-18	Instrumented roof bolt (after Signer and Jones 1990).....	35
Figure 2-19	A tell-tales (after Altounyan et al., 1997) .....	37
Figure 2-20	Numerical methods in rock engineering.....	37
Figure 2-21	Bolt pattern (after Spann and Napier, 1983) .....	41
Figure 2-22	Deflection compared to number of bolts (after Spann and Napier, 1983).....	42
Figure 2-23	A typical plate load versus time in South African collieries (after Canbulat et al., 2003) .....	49
Figure 3-1	Graphic representation and explanation of a typical geological profile, support type and final roof strata behaviour.....	59
Figure 3-2	Colliery 'A' site 1 (bord).....	63
Figure 3-3	Colliery 'A' site 2 (bord).....	64
Figure 3-4	Colliery 'B' area 1 site 1 (intersection).....	66
Figure 3-5	Colliery 'B' area 1 site 2 (roadway) .....	67
Figure 3-6	Colliery 'B' area 1 site 3 (roadway) .....	68
Figure 3-7	Colliery 'B' area 2 site 1 (intersection).....	69



Figure 3-8	Colliery 'B' area 2 site 2 (roadway) .....	70
Figure 3-9	Colliery 'B' area 2 site 3 (roadway) .....	71
Figure 3-10	Colliery 'B' comparative roof behaviour.....	73
Figure 3-11	Colliery 'B' comparison between roadway and intersection roof skin displacement .....	75
Figure 3-12	Colliery 'B' area 1 site 1 (intersection) collar anchor displacement.....	75
Figure 3-13	Colliery 'B' area 1 site 1 collar anchor velocity.....	76
Figure 3-14	Colliery 'C' site 1 (intersection).....	78
Figure 3-15	Colliery 'C' site 2 (roadway) .....	79
Figure 3-16	Colliery 'C' site 3 (intersection).....	80
Figure 3-17	Colliery 'C' site 4 (roadway) .....	81
Figure 3-18	Colliery 'C' comparative roof behaviour .....	82
Figure 3-19	Colliery 'D' area 1 site 1 (intersection) .....	85
Figure 3-20	Colliery 'D' area 1 site 2 (roadway) .....	86
Figure 3-21	Colliery 'D' area 1 site 3 (intersection) .....	87
Figure 3-22	Colliery 'D' area 1 site 4 (roadway) .....	88
Figure 3-23	Colliery 'D' area 1 comparative roof behaviour .....	89
Figure 3-24	Colliery 'D' area 1 comparison of roof skin displacement .....	90
Figure 3-25	Colliery 'D' area 2 site 1 (intersection) .....	92
Figure 3-26	Colliery 'D' area 2 site 2 (intersection) .....	93
Figure 3-27	Colliery 'D' area 2 site 3 (intersection) .....	94
Figure 3-28	Colliery 'D' area 2 site 4 (intersection holed into).....	95
Figure 3-29	Colliery 'D' area 2 site 5 (roadway approaching dyke).....	97
Figure 3-30	Colliery 'D' area 2 comparative roof behaviour .....	98
Figure 3-31	Colliery 'D' area 2 comparison between roadway and intersection roof skin displacement .....	99
Figure 3-32	Colliery 'D' area 3 site 1 (intersection) .....	100
Figure 3-33	Colliery 'D' area 3 site 2 (roadway) .....	101
Figure 3-34	Colliery 'D' area 3 site 3 (roadway blind end holed into).....	102
Figure 3-35	Colliery 'D' area 3 comparative roof behaviour .....	103
Figure 3-36	Colliery 'E' site 1 (gate road).....	107
Figure 3-37	Colliery 'E' site 2 (gate road).....	108
Figure 3-38	Colliery 'E' site 3 (split between gate roads) .....	109
Figure 3-39	Colliery 'E' site 4 (gate road).....	110
Figure 3-40	Colliery 'E' site 5 (roadway).....	111
Figure 3-41	Colliery 'D' area 2 site 2 displacements .....	116
Figure 3-42	Mining method and comparative support performance at Colliery 'D'.....	118
Figure 3-43	Instrumentation layout.....	120



Figure 3-44	Roadway and adjacent intersections prior to widening .....	122
Figure 3-45	Cutting sequence and final roadway shape .....	123
Figure 3-46	Increase in roof deflection with widening of roadway .....	125
Figure 3-47	Roof behaviour of the 12 m widened roadway with time .....	125
Figure 3-48	Separation within the roof beam with time .....	126
Figure 3-49	Displacement rates as a function of time .....	126
Figure 3-50	Experiment site taken on day nine .....	129
Figure 4-1	Cutting and instrumentation sequence in CM sections .....	139
Figure 4-2	Cutting and instrumentation sequence in road header sections .....	140
Figure 4-3	a) Probable cause of observed roof damage. b) Probable cause of observed roof bolt defects (after van der Merwe, 1998) .....	141
Figure 4-4	Summary of underground stress mapping techniques (after Mark and Mucho, 1994) .....	142
Figure 4-5	Colliery 'A' Site 1, Test 1 .....	149
Figure 4-6	Colliery 'A' Site 1, Test 2 .....	150
Figure 4-7	Colliery 'A' Site 2 .....	151
Figure 4-8	Colliery 'A' Site 3 .....	152
Figure 4-9	Colliery 'B' Site 1 .....	157
Figure 4-10	Colliery 'B' Site 2 .....	158
Figure 4-11	Colliery 'B' Site 3 .....	159
Figure 4-12	Colliery 'C' Site 1 .....	164
Figure 4-13	Colliery 'C' Site 2 .....	165
Figure 4-14	Colliery 'C' Site 3 .....	166
Figure 4-15	Colliery 'D' Site 1 .....	169
Figure 4-16	Colliery 'E' Site 1 .....	172
Figure 4-17	Colliery 'F' Site 1 .....	175
Figure 4-18	The relationship between the support density and total displacement.....	177
Figure 4-19	The relationship between the thickness of the immediate layer and total displacement .....	177
Figure 4-20	The relationship between the bord width and total displacement .....	178
Figure 4-21	The relationship between the cut-out distance and total displacement.....	178
Figure 4-22	The relationship between the thickness of the immediate layer obtained from the borehole logs and height of the displacement obtained from underground sites where some degree of dilation was recorded .....	179
Figure 4-23	Relationship between measured and predicted dilation.....	181
Figure 4-24	MAP3D model that was used in the numerical modelling analysis .....	184
Figure 4-25	Effect of bord width on dilation .....	185
Figure 4-26	Effect of k-ratio on roof deformations .....	186



Figure 4-27	Effect of the thickness of the immediate layer on roof deformations.....	187
Figure 4-28	Effect of the strength of the immediate layer on roof deformations.....	188
Figure 5-1	Components of the CMRR system (after Mark and Molinda, 1994) .....	196
Figure 5-2	Cores used for CMRR and impact splitting testing .....	200
Figure 5-3	The Impact splitting equipment .....	205
Figure 5-4	Impact splitting unit rating calculation .....	205
Figure 5-5	A fine to medium grained sandstone or “grit” unit before impact splitting, taken from borehole ARN 4968.....	212
Figure 5-6	A fine to medium grained sandstone or “grit” unit after impact splitting, taken from borehole ARN 4968 .....	212
Figure 5-7	Borehole drill core from Colliery ‘B’, No 5 Seam .....	215
Figure 5-8	Borehole drill core from Colliery ‘B’, No 2 Seam .....	216
Figure 5-9	Typical Colliery ‘K’ No 4 Seam roof lithology .....	222
Figure 6-1	Form used for recording data from equipment tests .....	231
Figure 6-2	Drilling speed - bolter A.....	232
Figure 6-3	Drilling speed - bolter B.....	233
Figure 6-4	Drilling speed - other bolters .....	233
Figure 6-5	Drilling speed - all bolters.....	234
Figure 6-6	Resin spinning speed - bolter A .....	235
Figure 6-7	Resin spinning speed - bolter B .....	235
Figure 6-8	Resin spinning speed - other bolters.....	236
Figure 6-9	Resin spinning speed - all bolters .....	236
Figure 6-10	Torque - bolter A .....	237
Figure 6-11	Torque - bolter B .....	238
Figure 6-12	Torque - other bolters.....	238
Figure 6-13	Torque - all bolters .....	239
Figure 6-14	Thrust - bolter A .....	240
Figure 6-15	Thrust - bolter B .....	240
Figure 6-16	Thrust - other bolters.....	241
Figure 6-17	Thrust - all bolters .....	241
Figure 6-18	Hole profile standard deviation frequency.....	243
Figure 6-19	Drilling speed against hole profile standard deviation.....	243
Figure 6-20	Torque against hole profile standard deviation .....	244
Figure 6-21	Thrust against hole profile standard deviation .....	245
Figure 6-22	Drilling Speed against hole profile standard deviation in machines using wet flushing system .....	246
Figure 6-23	Drilling speed against hole profile standard deviation in machines using dry flushing system .....	247



Figure 6-24	Torque against hole profile standard deviation in machines using dry flushing system .....	248
Figure 6-25	Resin spinning speed against hole profile standard deviation in machines using wet flushing system .....	248
Figure 6-26	Hole profile standard deviation in sandstone .....	249
Figure 6-27	Hole profile standard deviation in 'soft' materials .....	250
Figure 6-28	Effect of wet-dry drilling.....	251
Figure 6-29	Effect of wet and dry drilling on overall support stiffness .....	251
Figure 6-30	Performance of roof bolts determined from underground SEPTs.....	253
Figure 6-31	Effect of tensioning on bond strength.....	254
Figure 6-32	Effect of tensioning on overall stiffness.....	255
Figure 6-33	Roof bolt diameter deviations in bolts from three different manufacturers.....	257
Figure 6-34	Roof bolt rib-height measurements in bolts from three different manufacturers.....	258
Figure 6-35	Visual illustration of four South African roof bolts.....	259
Figure 6-36	Visual comparison of UK and South African bolts.....	260
Figure 6-37	Performance of 15-second and 30-second resin types in sandstone from both resin manufacturers .....	261
Figure 6-38	Performance of 15-second and 30-second resin types in shale from both resin manufacturers .....	262
Figure 6-39	Performance of 15-second and 30-second resin types in coal from both resin manufacturers .....	262
Figure 6-40	System stiffness of 15-second and 30-second resin types from both resin manufacturers .....	263
Figure 6-41	Simplified drawing of roof bolt profile components.....	265
Figure 6-42	Simplified drawing of failure between the rock and the resin .....	266
Figure 6-43	Effect of rib angle on pull-out loads (simplified) .....	268
Figure 6-44	Spade and 2-prong bits (25 mm) .....	268
Figure 6-45	Performance of spade bit and 2-prong bit.....	269
Figure 6-46	Hole annuli obtained from the 2-prong and spade bits .....	270
Figure 6-47	Overall stiffnesses obtained from the 2-prong and spade bits .....	270
Figure 6-48	Effect of hole annulus on bond strength.....	272
Figure 6-49	Effect of rock type on support performance .....	273
Figure 7-1	Hypothetical distribution of the strength and the load .....	290
Figure 7-2	Hypothetical distribution of the safety margin, SM.....	291
Figure 7-3	Measured height of roof-softening in intersections and roadways in South African collieries .....	298
Figure 7-4	An example of roof-softening in a coal mine in the USA (courtesy of Dr. C. Mark) .....	299



Figure 7-5	The vertical dimension (thickness) of FOG causing fatalities for the period 1970 – 1995 .....	300
Figure 7-6	Cumulative distribution of FOG thicknesses and the height of roof softening measured underground.....	300
Figure 7-7	Measured deformations in intersections and roadways .....	301
Figure 7-8	Zone of roof softening .....	302
Figure 7-9	Beam with transverse shear force showing the transverse shear stress developed by it.....	306
Figure 7-10	Computation and distribution of shear stress in a beam .....	307
Figure 7-11	Bed separation within the bolted horizon .....	309
Figure 7-12	Recommended support design methodology.....	319
Figure 7-13	Colliery “A” height of softening data obtained from the sonic probe extensometer results, feeler-gauge results and FOG data .....	321
Figure 7-14	Bord width distributions in the experiment site.....	321
Figure 7-15	Thickness of immediate and upper roof obtained from borehole logs .....	322
Figure 7-16	Bond strength results obtained from SEPT in the experiment site.....	323
Figure 7-17	Distribution of roof bolting tensioning results .....	324
Figure 7-18	Distance between the roof bolts measured in the experiment site.....	324
Figure 7-19	Roof bolt ultimate strength .....	325
Figure 7-20	Distribution of tensile strength of coal used in the analysis.....	326
Figure 7-21	Unit weights of the immediate and upper coal layers.....	326
Figure 7-22	Distribution of coefficient of friction between the layers .....	327
Figure 7-23	Distribution of safety factors of upper coal layer in suspension mechanism ...	329
Figure 7-24	Distribution of safety factors in suspension mechanism using 1.2 m long roof bolts .....	329
Figure 7-25	PoS and Reliability Index for suspension mechanisms for different roof bolt lengths .....	330
Figure 7-26	Probability of stability and reliability index of different length roof bolts, 3 roof bolts in a row .....	331



## List of Tables

Table 2-1	Support system characteristics summary (after van der Merwe and Madden, 2002) .....	21
Table 2-2	Support system suitability (after van der Merwe and Madden, 2002) .....	22
Table 2-3	Bolt types commonly used in the U.S.A mines (after Peng, 1984) .....	24
Table 3-1	Sonic probe, levelling and stable roof elevation results .....	58
Table 3-2	Total relaxation and stable roof elevation averages.....	113
Table 4-1	Distribution of test sites .....	137
Table 4-2	Site performance Colliery 'A' Site 1, Test 1.....	144
Table 4-3	Site performance Colliery 'A' Site 1, Test 2.....	145
Table 4-4	Site performance Colliery 'A' Site 2.....	146
Table 4-5	Site performance Colliery 'A' Site 3.....	148
Table 4-6	Site performance Colliery 'B' Site 1.....	153
Table 4-7	Site performance Colliery 'B' Site 2.....	155
Table 4-8	Site performance Colliery 'B' Site 3.....	156
Table 4-9	Site performance Colliery 'C' Site 1.....	160
Table 4-10	Site performance Colliery 'C' Site 2.....	162
Table 4-11	Site performance Colliery 'C' Site 3.....	163
Table 4-12	Site performance Colliery 'D' Site 1.....	168
Table 4-13	Site performance Colliery 'E' Site 1 .....	170
Table 4-14	Site performance Colliery 'F' Site 1 .....	173
Table 4-15	Summary results obtained from No 1 sonic probe monitoring holes.....	182
Table 4-16	Summary results obtained from No 2 sonic probe monitoring holes.....	183
Table 4-17	Input parameters used in numerical modelling .....	184
Table 5-1	CMRR classes in the U.S. (after Mark and Molinda, 1994) .....	197
Table 5-2	A summary of some classification systems used in South African coal mining and their main applications .....	202
Table 5-3	Description of sedimentary facies and summary of their underground properties .....	203
Table 5-4	Unit and coal roof classification system (after Latilla et al, 2002) .....	206
Table 5-5	Estimated support requirements for different roof classifications (after van Wijk, 2004) .....	207
Table 5-6	Roof grit hazard classification used at Colliery 'A' .....	211
Table 5-7	Impact splitting results at Colliery 'A', No 2 Seam, borehole ARN 4968 .....	213
Table 5-8	Impact splitting results at Colliery 'A', No 2 Seam, borehole ARN 4974 .....	213
Table 5-9	Impact splitting results at Colliery 'A', No 2 Seam, borehole ARN 4975 .....	214
Table 5-10	Roof hazard classification at Colliery 'B' .....	215





Table 5-11	Impact splitting results at Colliery 'B', No 5 Seam, borehole H45S5.....	216
Table 5-12	Impact splitting results at Colliery 'B', No 5 Seam, borehole H49S5.....	217
Table 5-13	Impact splitting results at Colliery 'B', No 5 Seam, borehole H50S5.....	218
Table 5-14	Impact splitting results at Colliery 'B', No 2 Seam, borehole P4S2.....	218
Table 5-15	Impact splitting results at Colliery 'B', No 2 Seam, borehole P3S2.....	219
Table 5-16	Guidelines used in hazard plan at Colliery 'T' .....	219
Table 5-17	Impact splitting results at Colliery 'T', No 4 Seam, borehole G293584 .....	220
Table 5-18	Impact splitting results at Colliery 'T', No 4 Seam, borehole G293585 .....	220
Table 5-19	Impact splitting results at Colliery 'T', No 4 Seam, borehole G293587 .....	221
Table 5-20	Impact splitting results at Colliery 'T', No 4 Seam, borehole G293588 .....	221
Table 5-21	Composite roof hazard plan classification at Colliery 'K' .....	222
Table 5-22	Impact splitting results at Colliery 'K', No 4 Seam, borehole KRL3811.....	223
Table 5-23	Impact splitting results at Colliery 'N', No 4 Seam, borehole 321 .....	224
Table 5-24	Impact splitting results at Colliery 'S', No 4 Seam, Borehole V118043.....	224
Table 5-25	Impact splitting results, borehole V118043 after coal adjustment factor.....	225
Table 6-1	Effect of wet and dry drilling (averages).....	252
Table 6-2	Performance of roof bolts determined from underground SEPTs (averages).	253
Table 6-3	Effect of tensioning on support performance (averages) .....	255
Table 6-4	Rib thickness, spacing and angle measured on South African roof bolts .....	259
Table 6-5	Overall stiffnesses of resin determined from underground SEPTs (averages)	264
Table 6-6	Performance of bit using SEPT (averages).....	271
Table 6-7	A list of direct controllables .....	274
Table 7-1	Acceptance probability of failures for different safety class (after Vrijling and van Gelder, 1998) .....	296
Table 7-2	Acceptance criteria for rock slopes (after Priest and Brown, 1983; Pine, 1992)	296
Table 7-3	Examples of design criteria for open pit walls (after DME, 1999) .....	297
Table 7-4	Suggested design criteria for the roof bolting systems .....	297
Table 7-5	Results of shear box tests on various contacts typically found in coal mines .	308
Table 7-6	Summary of probability distributions (after EasyFit user manual, 2006).....	313
Table 7-7	Summary results of Anderson-Darling goodness of fit tests .....	317
Table 7-8	Summary of information used in the analysis .....	327
Table 7-9	Stability analyses of different support patterns .....	332



## Glossary

### Abbreviations

2D	two dimensional
3D	three dimensional
BTS	Brazilian Tensile Strength
CM	continuous miner
CMRR	coal mine roof rating
D&B	drill and blast
DME	Department of Minerals and Energy
FOG	fall of ground
GP	grip factor
IST	impact split test
ISR	impact splitting unit rating
PoF	probability of failure
PoS	probability of stability
RMR	rock mass rating
RQD	rock quality designation, usually determined by accumulating all pieces of core greater than 100 mm in a borehole and expressing the value as a percentage of the length of hole or portion of the hole
SM	safety margin
UCS	uniaxial compressive strength
UTS	ultimate tensile strength

### Symbols and technical terms

$\rho$	the density of rock
$\mu$	coefficient of friction between the layers
$\tau_{max}$	maximum shear stress



$\sigma_1$	in rock testing, commonly the axial stress
$\sigma_1, \sigma_2$ and $\sigma_3$	major, intermediate and minor principal stress
$\sigma_{xx}$	maximum tensile stress
$\sigma_3$	in rock testing, commonly the confining stress
$\beta$	reliability index
$\eta_{max}$	maximum deflection
$\tau$	contact shear strength
abutment	the solid area at the edge of a mined out area
bord	roadway driven in orebody or seam and specially defined as that area between two pillars, which is not included in the definition of an intersection
$B$	bord width
$B_s$	bond strength
core	cylindrical shaped rock retrieved from a borehole
$D$	nominal diameter of the anchor or borehole
$d$	distance between the rows of roof bolts
density	mass per unit volume
discontinuity	geological or mining induced breaks in the rock mass
$E$	elastic modulus
extensometer	measures deformation within the rock mass by means of anchors placed within a borehole
extraction ratio	the ratio of mined to unmined ground
face	the end of a panel which is advanced during mining
floor	the rock mass below the excavation
fracturing	discontinuities forming as a result of mining
$g$	gravitational acceleration (9.81 m/sn <sup>2</sup> )
geomechanical testing	test to determine the physical properties of a geological material
geotechnical condition	an evaluation of the nature and condition of the geological discontinuities and rock material contained in a rock mass
$G(X)$	performance function

$h$	mining height
$h_1$	height of roof softening
intersection	The area where two roadways meet or cross one another
ISRM standards	international standards for rock mechanics tests set by the International Society of Rock Mechanics
joint	geological discontinuity
k-ratio	the ratio between the horizontal and vertical stress
$L$	span
$L_b$	distance between the bolts
$l_b$	bond length
$n$	number of bolts per square meter
$N_{mc}$	number of Monte Carlo trials
panel	span between the barrier pillars
panel span	the mined out span between two adjacent lines of barrier pillars or abutments
phi ( $\phi$ )	friction angle
point anchor	a roof bolt anchoring system where the anchor is in contact with the strata for a relatively short distance.
Poisson's ratio	lateral strain divided by axial strain, lateral strain being the result of an axial stress
roadway	an excavation developed in a coal seam, which encompasses both a bord and an intersection
roof	the rock mass above the excavation
roof bolt	a steel tendon anchored chemically (resin) or mechanically complete with a nut washer and meeting performance specifications
$SF_{sus}$	safety factor in suspension mechanism
$SF_{beam}$	safety factor in beam building mechanism
$SF_{slide}$	roof bolt sliding safety factor
$S_B$	ultimate tensile strength of a bolt



spalling	slabs that develop as a result of stress or time
span	the shortest distance between in-panel pillars or faces
tensile stress	normal stress tending to lengthen a body along the direction in which it acts
$t_{com}$	competent layer thickness
$t_{lam}$	laminated lower strata thickness
$T_R$	frictional shear resistance of tensioned roof bolts
$T_B$	shear resistance generated by the bolts
tensile zone	a tensile stress field that develops above a panel as a result of mining
unit weight	the weight per unit volume.
$V$	shear force
$V_{max}$	maximum shear force
Young's modulus (E)	stress divided by the strain resulting from the stress