

# Support of Underground Excavations in Hard Rock



**E. Hoek • P.K. Kaiser • W.F. Bawden**



# Table of contents

<b>Foreword</b>	<b>IX</b>
<b>Preface</b>	<b>XI</b>
<b>1 An overview of rock support design</b>	<b>1</b>
1.1 Introduction	1
1.2 Stages in mine development	1
1.2.1 Exploration and preliminary design	3
1.2.2 Mine design	3
1.2.3 Early years of mining	4
1.2.4 Later years of mining	5
1.3 Support design	7
<b>2 Assessing acceptable risks in design</b>	<b>8</b>
2.1 Introduction	8
2.2 Factor of safety	9
2.3 Sensitivity studies	10
2.4 The application of probability to design	10
2.5 Probability of failure	15
2.6 Problems to which probability cannot be applied	18
<b>3 Evaluation of engineering geological data</b>	<b>20</b>
3.1 Introduction	20
3.2 Engineering geological data collection	20
3.3 Structural geological terms	21
3.4 Structural geological data collection	22
3.5 Structural geological data presentation	23
3.6 Geological data analysis	24
<b>4 Rock mass classification</b>	<b>27</b>
4.1 Introduction	27
4.2 Engineering rock mass classification	27
4.2.1 Terzaghi's rock mass classification	28
4.2.2 Classifications involving stand-up time	29
4.2.3 Rock quality designation index ( <i>RQD</i> )	29
4.2.4 Rock structure rating ( <i>RSR</i> )	31
4.3 Geomechanics classification	33
4.4 Modifications to <i>RMR</i> for mining	37
4.5 Rock tunnelling quality index, <i>Q</i>	37
4.6 Using rock mass classification systems	44
4.7 Estimation of in situ deformation modulus	45
<b>5 Shear strength of discontinuities</b>	<b>48</b>
5.1 Introduction	48
5.2 Shear strength of planar surfaces	48
5.3 Shear strength of rough surfaces	49
5.3.1 Field estimates of <i>JRC</i>	51

5.3.2	Field estimates of <i>JCS</i>	52
5.3.3	Influence of scale on <i>JRC</i> and <i>JCS</i>	52
5.4	Shear strength of filled discontinuities	53
5.5	Influence of water pressure	53
5.6	Instantaneous cohesion and friction	54
<b>6</b>	<b>Analysis of structurally controlled instability</b>	<b>57</b>
6.1	Introduction	57
6.2	Identification of potential wedges	57
6.3	Support to control wedge failure	61
6.3.1	Rock bolting wedges	61
6.3.2	Shotcrete support for wedges	63
6.4	Consideration of excavation sequence	64
6.5	Application of probability theory	65
<b>7</b>	<b>In situ and induced stresses</b>	<b>66</b>
7.1	Introduction	66
7.2	In situ stresses	66
7.2.1	The World Stress Map	67
7.2.2	Developing a stress measuring programme	72
7.3	Analysis of induced stresses	73
7.3.1	Numerical methods of stress analysis	75
7.3.2	Two-dimensional and three-dimensional models	80
7.3.3	Stress analysis using the program PHASES	81
<b>8</b>	<b>Strength of rock and rock masses</b>	<b>84</b>
8.1	Introduction	84
8.2	Definition of the problem	84
8.3	Strength of intact rock	85
8.4	The strength of jointed rock masses	89
8.5	Use of rock mass classifications for estimating <i>GSI</i>	92
8.6	When to use the Hoek-Brown failure criterion	97
<b>9</b>	<b>Support design for overstressed rock</b>	<b>99</b>
9.1	Introduction	99
9.2	Support interaction analysis	99
9.2.1	Definition of failure criterion	101
9.2.2	Analysis of tunnel behaviour	101
9.2.3	Deformation of an unsupported tunnel	102
9.2.4	Deformation characteristics of support	104
9.2.5	Estimates of support capacity	106
9.2.6	Support interaction example	107
9.3	The PHASES program	107
9.3.1	Support interaction analysis using PHASES	109
<b>10</b>	<b>Progressive spalling in massive brittle rock</b>	<b>112</b>
10.1	Introduction	112
10.2	Examples of spalling in underground excavations	112
10.3	The AECL Underground Research Laboratory	114
10.3.1	In situ stresses at 420 level	115
10.3.2	Properties of Lac du Bonnet granite	115
10.3.3	URL Rooms 413 and 405	116
10.3.4	URL Test tunnel	118

10.4	Example from El Teniente Mine, Chile	119
10.5	South African experience	120
10.6	Implications for support design	124
10.6.1	Rockbolting	124
10.6.2	Shotcrete	125
10.6.3	Discussion	125
<b>11</b>	<b>Typical support applications</b>	<b>127</b>
11.1	Introduction	127
11.2	'Safety' support systems	127
11.3	Permanent mining excavations	131
11.4	Drawpoints and orepasses	132
11.5	Small openings in blocky rock	136
11.6	Small openings in heavily jointed rock	138
11.7	Pre-support of openings	142
11.7.1	Cut and fill stope support	143
11.7.2	Pre-reinforcement of permanent openings	146
11.7.3	Reinforcement of non-entry stopes	149
<b>12</b>	<b>Rockbolts and dowels</b>	<b>152</b>
12.1	Introduction	152
12.2	Rockbolts	152
12.2.1	Mechanically anchored rockbolts	152
12.2.2	Resin anchored rockbolts	156
12.3	Dowels	158
12.3.1	Grouted dowels	158
12.3.2	Friction dowels or 'Split Set' stabilisers	159
12.3.3	'Swellex' dowels	160
12.4	Load-deformation characteristics	161
<b>13</b>	<b>Cablebolt reinforcement</b>	<b>165</b>
13.1	Introduction	165
13.2	Cablebolt hardware	165
13.3	Cablebolt bond strength	167
13.4	Grouts and grouting	168
13.5	Cablebolt installation	171
13.6	Modified cablebolts	174
<b>14</b>	<b>The Stability Graph method</b>	<b>176</b>
14.1	Introduction	176
14.2	The Stability Graph method	176
14.2.1	The stability number, $N'$	176
14.2.2	The shape factor, $S$	180
14.2.3	The stability graph	180
14.3	Cablebolt design	181
14.4	Discussion of the method	182
14.5	Worked stability graph example	182
14.5.1	Structural geology	183
14.5.2	$Q'$ classification	183
14.5.3	Preliminary stope design	184
<b>15</b>	<b>Shotcrete support</b>	<b>190</b>
15.1	Introduction	190

15.2 Shotcrete technology	190
15.2.1 Dry mix shotcrete	190
15.2.2 Wet mix shotcrete	191
15.2.3 Steel fibre reinforced microsilica shotcrete	192
15.2.4 Mesh reinforced shotcrete	194
15.3 Shotcrete application	195
15.4 Design of shotcrete support	198

<b>References</b>	201
-------------------	-----

<b>Software information</b>	209
-----------------------------	-----

<b>Author index</b>	211
---------------------	-----

<b>Subject index</b>	213
----------------------	-----