A review of mechanized versus handheld bolting in hard rock tabular orebodies

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Synopsis

Mechanization in low-stope panels situated in hard rock infers roof support by tensile bolting to allow free passage of trackless mining equipment in the production areas. This is in sharp contrast to conventional mining, where compressive roof supports—such as timber and grout packs—have traditionally been used, up to 1.5 metres from the production face.

Bolting is a hazardous operation because material is dislodged from the roof during the drilling activity. Even with temporary roof support installed, small pieces of rock are dislodged by the percussive action of the drifter. Operations with the man situated directly under the drill, during the drilling activity, are hazardous. The only way to remove the hazard is to move the man away from the machine for as much as possible throughout the complete cycle. Costs associated with safety cannot be quantified, but need to form part of the decision-making process.

Machine selections based on purchase and running costs alone do not justify the investment cost of mechanized bolters. The equipment selection process needs to take into account the total cost of mining as well as the human safety impact and loss of production costs from having to re-bolt roofs in a production panel to prevent falls of ground.

Labour costs in mechanized low-stope bolting are between one-quarter and half the labour costs of non-mechanized bolting.

This paper reviews the mechanized bolting option versus handheld bolting from a mining process and cost perspective in a hard rock, low-stope room-and-pillar mining operation in the platinum and chrome industries.

Introduction

In this document two viable bolting models are considered; these are mechanized bolters and handheld or portable pneumatic bolters.

Mechanized bolting utilization is tabulated from data for a dedicated bolting machine in a single mining section (Pickering, 2003). The remaining mechanized bolting data used in this paper are based on units tested in the mines with norite and pyroxenite roofs.

Similar data on utilization were not available at the time of writing for pneumatic bolters and estimations were made using site reported performance and manufacturers' figures (Menasce, 2004b).

In a mechanized stope the face drill rig has the highest utilization. The bolters and loaders will have lower utilizations. Consequently, a dedicated production face drill cannot be used for bolting and face drilling.

Basis of mine model for bolting

The mine feasibility model used for this paper required:

- three production panels in any section to be bolted during a shift
- face advance of 2.5 to 2.8 metres per blast
- panel width of 12 metres
- approximately 10 to 12 roof bolts per panel per shift to be installed on a 2 x 2 metre spacing
- the total number of roof bolts needed to be installed per section amounts to between 30 and 36 roof bolts per shift per section of 12 metre panel. (This quantity is used in the model.)
- the total annual usage of roof bolts required to be installed in a full production section, based on a 2 x 2 metre bolting pattern, two shifts per day and 21 working days per month of operation, equates to between 15 000 and 18 000
- the mine has 7 production sections producing 100 000 tons per month.

If a 1.5 x 1.5 metre spacing is required, the number of bolts increases to 40 000 bolts per annum per section.

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Handheld pneumatic bolting

Bolting method

Handheld pneumatic rock drills are used to drill the roof, making use of a parallel telescopic jack leg for support. As the perpendicularity of the hole is controlled by the operator, the integrity of the bolting is dependent upon the operator's skill (Figure 1).

Safety considerations

The writer observed that during the bolting cycle rubble dislodges from the roof while the operator of a handheld machine is situated underneath. This raises a serious safety consideration.

Temporary roof support is required for the crew using 'camloc' or other temporary mechanical props or netting. Temporary roof support means that the trackless section being bolted is closed to vehicle access while the bolting process is in progress.

Performance and costs

A time-and-motion study of this system revealed that to drill a single 28 mm diameter hole, 1.8 metres deep in norite takes 5 minutes, taking into account the time required to set up the equipment, the collaring process, and inserting the resin and bolts. This is followed later by a second crew coming to fully tighten the bolts. The bolting rate is 4 bolts per hour.

The time-and-motion study revealed that the pneumatic bolter can be operated by two men in theory but a crew of up to four is required to manoeuvre the bolter and the hoses in difficult conditions.

No life-cycle models were available on the pneumatic bolter, therefore the estimated figures used are based on feedback from the Two Rivers operation and discussions with other end-users in the industry.

Figure 1—Handheld bolting rig

The running costs per annum on handheld bolters are equivalent to the purchase costs of the bolter (R7 500 + R7 500).

The bolting rate for pneumatic systems is 4 bolts per hour per machine for a 1.8 metre bolt.

Compressed air consumption is 5 600 *l*/m (200 cfm) per bolter at 0.4 MPa (4 bar).

Compressed air consumption excluding all losses totals 117 600 *l*/m (4 200 cfm) for the fleet.

Tabulated cost summaries are shown in Table I.

Reticulated air-supply installation costs

A computerized model of the mine air reticulation (Kempson, 2004) for 117 600 *l*/m (for seven operating sections) is shown in Table II based on a centralized compressed air installation. Inclusive of line pressure losses and leakages, this layout resulted in 3 x 42 000 *l*/m compressors operating 24 hours per day, with one unit on standby.

Total installation cost for reticulated compressed air system

The study assumed that the screw compressors require replacement every 5 years (40 000 running hours). In all probability, the compressor on its own would be replaced but the replacement cost of the compressor alone is in all likelihood similar to the original unit's installation cost. For the purposes of this study, it was assumed that the replacement cost of a screw compressor equates to the original purchase cost of such a unit (all studies based on 2004's money). (Tables III ,IV and V.)

The estimated equipment replacement cost during the sixth year (cost of compressors) is R2.0 M.

Severe gradients

On severe gradients (>14°), that could occur with a pot-hole or other geological discontinuity, handheld bolting may be the only option.

Mechanized hydraulic bolters

The principal dimensions of a Robolt LP bolter are given in Figure 2 .

Bolter utilization and operator safety considerations

One mechanized bolter (not 'fully mechanized'—see Glossary) can consistently, drill, insert and tighten 8 resin-grouted, 1.5 metre bolts per hour. The drilled holes' quality was always found to be perpendicular to the roof and the bolt torque is consistent due to the fact that it can be controlled during the installation process. This particular bolter is operated by two persons working in a supported area away from the drilling activity. The bolting head stakes the roof for drilling accuracy and the operator is situated away from the area being bolted as the actions are controlled by a cable-remote console. The only time an operator is exposed to the hole is when drill rod changes are required and during the insertion of a resin cartridge and the bolt into the hole.

If a fully mechanized bolter (with bolting carousel and resin-injection facilities) is considered then the operation is performed by one man who is situated consistently away from the bolting operation using the cable-remote console.

Table I

Handheld pneumatic bolting data

Item	Bolts per annum per section	Fleet (7 sections)
Bolts installed per annum (based on 4 bolts per hour)	15 000 to 18 000	105 000 to 126 000
Bolter purchase cost	R7 500 each	
Bolter unit life	6 months	
No. of units needed to operate	4 per section (3 operating 1 spare)	28
No. of units purchased annually (purchased 2 x per annum)	8 per section	56
Annual bolter purchase cost	R60 000	R420 000
Capital expenditure over 5 years	R300 000	R2.1 m
Estimated equipment annual running cost for installed bolts (R5.00 per bolt)	R75 000 for 15 000 bolts R90 000 for 18 000 bolts	R525 000 to R630 000
5-year running costs		R2.6 m to R3.2 m
Compressed air consumption excluding all losses	16 800 l/m per section	117 600 l/m for fleet

Table II

Compressed air reticulated model

Item	From	To	Horizontal length (m)	Vertical length (m)	Real length (m)	Diameter (m)	Cost/metre (m)	Total cost
1	Portal	Block 1A North	750	123	760	200	R220	R167 198
2	Block 1A North	Block 1 South	238	39	241	200	R220	R53 057
3	Block 1 South	Block 3 North	36	6	36	200	R220	R8 025
4	Block 3 North	Block 2 South	104	17	105	200	R220	R23 185
5	Block 2 South	Block 4 North	96	16	97	200	R220	R21 401
6	Block 4 North	Block 3 South	84	14	85	200	R220	R18 726
7	Block 3 South	Block 5 North	116	19	118	200	R220	R25 860
8	Block 1A North	End of strike	750	123	760	200	R220	R167 198
9	Block 1A South	End of strike	1000	Na	1000	150	R97	R97 000
10	Block 3 North	End of strike	2 500	Na	2 500	150	R97	R242 500
11	Block 2 South	End of strike	1000	Na	1000	150	R97	R97 000
12	Block 4 North	End of strike	2 500	Na	2 500	150	R97	R242 500
13	Block 3 South	End of strike	1000	Na	1000	150	R97	R97 000
14	Block 5 North	End of strike	2 500	Na	2 500	150	R97	R242 500
							Total	**R1 503 150**

Dip of decline 9.3°. Calculations based on maximum strike length

Table III

Centralized compressor and infrastructure costs

Item	Unit	Fleet
42 000 l/m screw compressor	R 500 000 each	R2 m (3 plus 1 standby)
Installation of compressor house		R250 000
Switchgear		R200 000
Pipe work (from Table II)		R1 503 000 m
Installation		Est. R100 000
Valves		Est. R200 000
Total initial capital costs		R4.26 m
Running cost	R48 000 p/a	R960 000 over 5 years
Total cost over first 5 years		R5.22 m

Table IV

Centralized compressor energy consumption

Item	Unit	Total
Electrical power required	300 kVA	900 kVA (3 units running)
24-hour electrical power consumption (based on 20 running hours per day)		18 MVAh
Annual power consumption (252 working days per annum)		4536 MVAh

Table V

Fleet data for handheld pneumatic bolter and centralized compressed air reticulation

Item	Total fleet
Capital bolter expenditure over 5 years (Table I)	R2.1 m
Estimated annual bolter running cost for 5 years (Table I)	R3 m
Centralized compressed air installation (4 screw compressors including maintenance) first 5 years	R5.22 m
5-year electricity consumption (est. at 20 c/kWh for 6 048 MVAh p/a)	R7.25 m
Total costs over first 5 years	R17.57 m

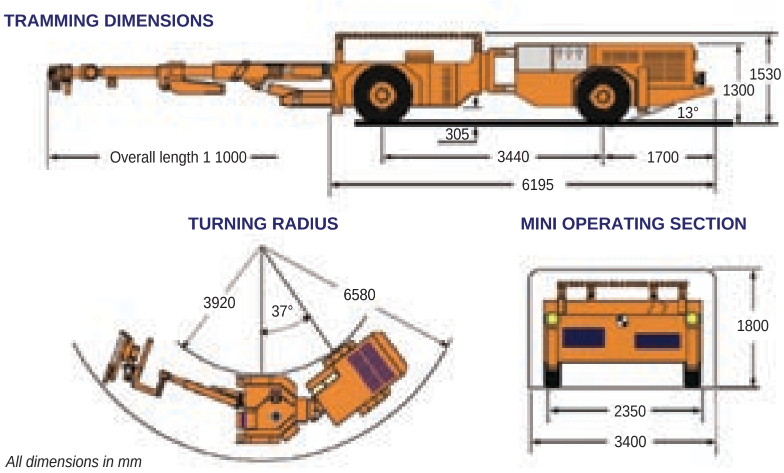

Figure 2—Principle dimensions Robolt LP

Based on a 2 x 2 metre bolting pattern, each production section needs 30 to 36 bolts per shift or 12 bolts per panel. The time-and-motion study revealed that it takes 8 bolts per hour and, therefore, 1.5 hour per panel or 4.5 hours per section.

Table VI illustrates extracts from Pickering's (2003) report on trials done with a fully mechanized bolter (see Glossary) operating in UG2.

Refer to the Glossary for the definitions used in Tables VI and VII.

Interpreting the results in Table VI and VII:

- the fully mechanized bolter has a higher bolting rate compared to the semi-mechanized bolter, as the drilling and bolt insertion process is performed more quickly (8 bolts per hour for the semi-mechanized bolter versus 10 to 12 bolts per hour for the fully mechanized bolter)
- an additional 15 to 20 per cent of the bolting activity time is needed for tramming for relocation to other panels and setting up of the mechanized bolter
- the challenge facing the end user is to provide enough face space for the bolter in order to improve its utilization time as the low utilization figures indicate that the bolter ran out of face to bolt.

For the model discussed, requiring 4.5 hours of actual bolting time, the total machine operating time per shift is between 4.5/0.85 = 5.2 hours and 4.5/0.8 = 5.6 hours for a complete section in this application based on an average of 8 bolts per hour for the standard model bolter and this gives an average utilization of between 55 per cent and 62 per cent, which compares with Pickering (2003).

It should be noted that the floor conditions will affect the bolting rate as the floor conditions will influence the ease of manoeuvring in the sections.

Increased bolting pattern or bolt length

The existing mine feasibility model is based on a 2 x 2 metre bolting pattern for a production stope; however, if this is reduced to a 1.5 metre pattern then the number of bolts that could be installed per section will increase to between 25 and 27 bolts per panel and the existing mechanized bolter will be required to operate for 10 bolting hours per day. This is clearly not possible. If such a situation occurs one of the solutions would be to make use of a fully mechanized bolter, resulting in an increase of the bolting rate, up to 12 bolts per hour. A fully mechanized bolter would be able to insert 70 to

Table VI

Fully mechanized bolter utilization data (Set 1)

Date	27/11	28/11	2/12	4/12	5/12	10/12	12/12
Shift time (hours)	11	10–50	15–30	8–00	8	8–30	8
Equipment inspection, delays and maintenance (hours)	0–20	1–40	0–20	0–20	1	0–20	0–20
Mining delays (hours)	6.2	3	5.7	3	5,2	2	2.6
Power pack (hours)	3.3	4.6	8.4	2.8	1.2	2	2.6
Engine (hours)	1.1	1.6	1.4	1.9	0.4	4.1	2.1
Percussion (hours)	0.6	0.7	0.8	1.3	0.2	0.1	0.4
Availability %	97	85	98	96	88	96	96
Utilization %	41	68	65	61	23	74	59
Bolting activity %	31	50	55	37	17	25	34
Bolts per shift	35	45	42	20	16	20	20
Bolts per power pack hour	10.6	9.8	5	7.1	13.3	10	7.7

Table VII

Fully mechanized bolter utilization data (Set 2)

Date	15/12	16/12	17/12	19/12	30/12	31/12	2/01
Shift time (hours)	9	8	9	9	9	9	9
Equipment inspection and delays and maintenance (hours)	0–20	0–20	0–20	0–20	0–20	0–20	0–20
Mining delays (hours)	4.2	5.2	3.4	5.9	3.4	2.2	4.1
Power pack (hours)	3.1	0.9	3.5	2.1	3	5.1	3.9
Engine (hours)	1.4	1.6	1.8	0.7	2.3	1.4	0.7
Percussion (hours)	0.5	0.2	0.3	0.2	0.3	1.6	0.4
Availability %	96	96	96	96	96	96	96
Utilization %	52	33	61	32	61	75	53
Bolting activity %	36	12	40	24	35	59	45
Bolts per shift	36	16	32	41	16	20	35
Bolts per shift power pack hour	11.6	17.7	9.1	19.5	5.3	3.9	9

80 bolts in a normal shift when compared to a mechanized bolter that is able to insert only 50 bolts in a normal shift at a best utilization time of 6 hours. However, a fully mechanized bolter, equipped with the current carousel design, would not be able to handle longer bolts than the stope width as coupled drill rod and coupled bolts would have to be accommodated in the carousel.

Bolter performance at Two Rivers

A Robolt LP (semi-mechanized) at Two Rivers has achieved the following results:

- 60 bolts installed per shift and a record of 130 bolts in 13 hours
- bolts are 1.5 metres long with full column resin grout
- holes drilled are 33 mm diameter, and resin cartridge is 25 mm diameter with M20 bolts.

Effective shift time and average bolting rate per hour were not available, therefore, these figures may appear optimistic and 8 bolts per hour will be used for this study.

However, what was observed by the authors is that the quality of installed bolts is consistently good when compared to the bolting installation making use of a pneumatic bolter.

Bolting costs Robolt LP

Bolter operating costs reflected below are per resin-grouted bolt installed, excluding consumable costs (drill string, bits, bolt and the resin cartridge).

Drilling consumable costs are R3.00 per metre for a 1.6 metre hole at 33 mm diameter to accommodate a full column, resin-grouted bolt. Bolter running costs are R51.35 per hole based over the life of the machine (Figure 3).

From Figure 3 (Mote and Comorge, 2004) it can be seen that the bolter running cost averages R410.35 per hour and R51.30 per bolt installed. This figure includes two machine refurbishments at 4 000 and 8 000 hours.

Estimating that 105 000 to 126 000 bolts per year are installed in seven operating sections, Table VIII summarizes the capital and running costs:

Rotary drilling versus roto-percussive drilling

The Robolt LP mechanized bolter is roto-percussive bolter and has a documented performance in chrome as well as at various platinum operations and consequently was considered as the benchmark for this study.

However, during the later compilation of the original study the writers were approached and shown bolting costs from a trial where a rotary bolter had operated for six months in the Rustenburg area, bolting in norite and pyroxenite hangings (Menasce, 2004a).

Despite the high usage of rotary bits, estimated at 6 holes per bit, both the projected drilling consumable cost and machine operating cost per bolt is lower for rotary than for roto-percussive drilling. In addition, the hole size drilled is 25 mm, requiring less resin per hole and better resin mixing with the smaller annulus between bolt and hole. As a consequence of the better mixing of the resin, the bolt installation quality is claimed to be higher for rotary-drilled holes than for roto-percussive drilled holes.

However, as the purpose of this paper is to examine the most expensive case study for mechanized bolting versus handheld bolting, the claimed reduced costs of rotary bolting serve only to strengthen the argument for mechanization.

Mechanized-bolting costs

Based on the previous discussions, the following model has been used for the mechanized bolting:

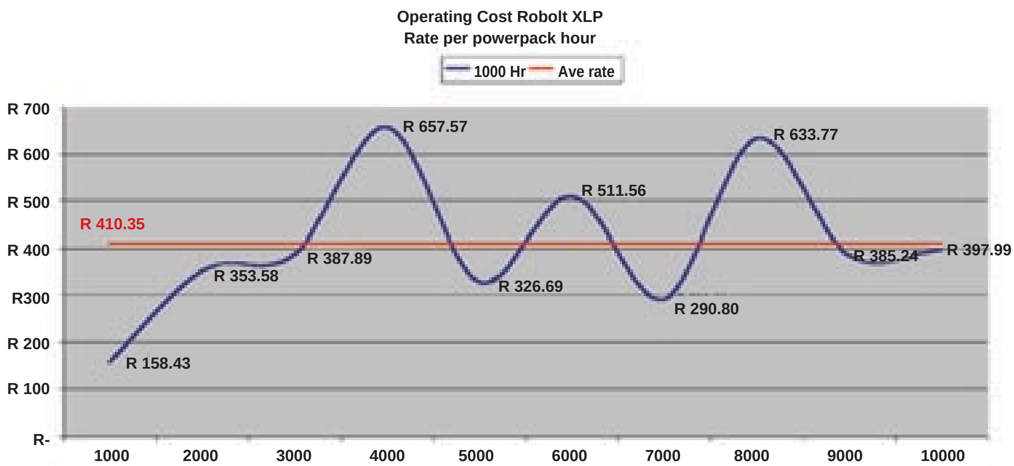

Figure 3—Life cycle costs of Robolt LP mechanized bolter

Table VIII

Robolt LP costing data

Item	Per machine	Total fleet 7 units
Capital expenditure over 5 years	R2 m	R14 m
Economic life	10 000 power-pack hours or 5 years	5 years
Life to overhaul	4 000 power-pack hours or 2 years	2 years
Annual operating hours	1 800 to 2 000	12 600 to 14 000
No. of bolts installed per year	15 000 to 18 000 per unit	105 000 to 126 000
Annual bolting cost at R51.30 per bolt	R770 000 to R923 000 per bolter	R5 39 m to R6 46 m
5-year bolting cost at R51.30 per bolt		R27 m to R32 m
Electrical power required	60 kW or 75 kVA	525 kVA
24-hour electrical power consumption (actual machine power pack utilization)		7.5 MVAh
Annual power consumption (252 working days)		1 890 MVAh

- One mechanized bolter is required per section
- The maximum bolting rate is 8 bolts per hour per machine and the bolting cycle takes 5 to 6.5 hours per section to install about 40 to 50 bolts
- Each mechanized bolter is operated by two men
- Machine life equates to 10 000 power-pack hours
- Life-in-service is estimated at 5 years.

Estimated employment cost, equipment operators

Table X gives a cost-to-company (CTC) comparison of machine operators for both pneumatic portable and mechanized bolting equipment for various bolting patterns Clegg (2004).

Financial implication of incorrectly installed bolts

Table XI gives estimated losses in production from incorrect bolting procedures. Losses for re-bolting the roof do not include unquantifiable losses from falls of ground in a production section. For this exercise it is assumed that manually installed, resin-grouted bolts with a pneumatic bolter have a 5 per cent higher reject rate than bolts installed by mechanized bolting.

Despite the simplicity of the revenue loss model used, the last line in Table XII indicates that the total mining process needs to be reviewed when evaluating bolting costs and not just the purchase price and running costs of a bolter operation. While loss of revenue can be calculated easily, the injury payouts and other softer HR issues are difficult to quantify. The costs of handheld bolting will, in practice, be far higher than the figures shown in Table XII.

Table IX

Summary of costs for mechanized bolting (no. of bolters)

Item	Fleet (7 units)
Purchase cost with replacement every 5 years	R14 m
Annual running costs (from SMC life cycle model)	R6 m
Total running costs over 5 years	R30 m
Total machine cost over 5 years	R44 m
Electricity consumption	1 890 MVAh per year
Electricity costs over 5 years (assumes 20 c/kWh)	R1.87 m
Total fleet operating cost over 5 years	**R45.8 m**

Conclusion

Roof bolting is a hazardous operation. The fewer persons who are involved in the bolting area and the further they are away from the drilling process, the safer the operation. The mechanized bolter cannot be justified on economic terms alone, but must be viewed in the bigger picture of operational safety and minimizing loss of revenue from re-supporting the roof in a production panel (Table XII).

The following additional points are necessary to give a full picture of the investment in mechanized bolting:

- In reviewing the scenario where the bolting density or the bolt length is increased, the mechanized bolter will need less change of mine infrastructure than the pneumatic bolter to accommodate these variations
- The author has observed that mechanized bolting provides consistent results
- Consistency of the bolts inserted is a prime safety consideration
- Projected loss of revenue from incorrectly installed bolts overshadows the increased capital purchase costs of the mechanized bolters.

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Table X

Comparison of labour per section semi skilled vs. mechanized with various bolting patterns

Operator category	Annual cost to company per employee	Personnel required/ section/day	Annual CTC per section 2004	5 year CTC per section in 2004 money at 10% wage increases
Bolting pattern at 2 metre centres Semi-skilled operators Portable and handheld bolters and roof support team	R70 447	Team of 4 per panel and 2 teams per section per shift 8 persons per shift Total of 16 persons per day	R1.13 m	R9.04 m
Bolting pattern at 1.5 metre centres Semi-skilled operators Portable and handheld bolters and roof support team	R70 447	Team of 4 per panel and 3 teams per section per shift 12 persons per shift Total of 24 persons per day	R1.69 m	R18.98 m
Bolting pattern at 2 metre or 1.5 metre centres Skilled operator and assistant Mechanized bolting operator	R130 923	One team of 2 persons per section per shift Total of 4 persons per day	R524 000	R5.86 m

Table XI

Loss of revenue from incorrect bolting

Item	Value
Tons mined per panel per blast	125 t
Tons mined per panel per day	250 t
Revenue per panel per day based on R150/ton of ROM	R37500
For 100 000 bolts per annum, if only 5% of all bolts inserted manually are faulty then	5000 faulty bolts affect 160 panels annually
Re-bolting time for 160 panel (drilling stopped while panel is re-bolted)	160 production shifts lost
Lost production revenue on 160 panels annually	R6 m
5-year revenue loss (900 panels)	R30 m

Table XII

Summary of estimated production bolting costs versus revenue loss over 5 years from re-bolting existing support

Bolting method	Total bolting cost over 5 years (taken from Tables III to V)	Operators labour costs over 5 years (taken from Table X)	5% loss of revenue from re-bolting (taken from Table XI)	Total costs (bolting cost plus loss of revenue)
Mechanized bolter	R45.8 m	R5.86 m	0	R51.66 m
Handheld bolter with centralized compressed air	R17.57 m	R9.04 m	R30 m	R56.6 m

2 x 2 metre pattern in production sections (not decline or strike development)

Appendices

Water services

4 bar water pressure is required at the faces for bolting for both the machine options considered and is not included in the trade-off study.

Change of bolting pattern and bolt length

Bolting pattern

Should the roof support requirements change to say a 1.5 metre pattern then the effective number of bolts per section will increase to 75 to 81 bolts inserted in a production section per shift.

It is worth noting that at Two Rivers, some areas of roof require a bolting pattern of 800 x 800 mm. Currently the only mechanized bolter capable of inserting 80 bolts per shift is the fully mechanized Robolt LP.

Increased bolt length

Change of bolt length will affect the bolting rate for two reasons:

- longer drilling time and
- the possibility of having to use coupled bolts if the bolt length is greater than the stope width.

As far as could be ascertained at the time of writing, no studies were available on the insertion rate of resin-grouted bolts longer than 1.5 metres. ◆

Glossary of terms	
Availability:	(shift time – machine delays)/shift time
Utilization:	(power pack + engine hours)/(shift time – machine delays)
Power pack hours:	Hours run by the mechanized bolter's hydraulic power pack during the actual bolting cycle. (Power pack is electrically driven)
Engine hours:	Hours run by the diesel engine when the bolter is tramming from one section to another (The electrically driven hydraulic power pack is switched off when the diesel engine is running)
Bolting activity:	(powerpack hours)/(shift time–machine delays)
Bolts per power pack hour:	Bolts per shift/power pack hours
Feed rail:	Guide rail system that carries the hydraulic drifter
Telescopic feed rail:	Guide rail system that can be extended or retracted hydraulically
Feed force:	Force provided by the feed rail on the drifter, or the extension leg on the pneumatic rockdrill to keep the drill bits in contact with the rock
Drifter:	Roto-percussive rockdrill powered by hydraulic oil
Shank bushing:	The bush that guides the reciprocating and rotating shank of the roto-percussive hydraulic drifter
Shank:	Adaptor for the drill rod
Boom:	Hydraulically powered arm that carries the feed rail
Staking:	Pushing a hydraulic or pneumatic ram against the roof to stabilize the feed rail that assists with accurate drilling of holes
Collaring:	The action of starting to drill a hole in rock face. When collaring, the feed force is reduced to get the hole started without the bit drifting erratically on the face and damaging either the drill string or the boom
Drill string:	The drill rod included with shank
Pneumatic bolter:	Bolting machine using compressed air to drive the rock drill and the extension rams. It could be a portable or self-propelled mobile machine
Mechanized bolter:	Roof bolter on a self-propelled mobile machine that uses a boom and feed rail with a dedicated bolting head in order to drill holes and insert and tighten roof bolts. The changing of the drill rods, insertion of the resin and the initial positioning of bolts in the hole are still performed by manual labour
Fully mechanized bolter:	A bolter as above, but equipped with a fully mechanized carousel carrying bolts and drill rods equipped with a mechanized rod changer, bolt handler and a mechanized resin injection system. All the operations are mechanized and controlled from a remote console by a single operator
Bolting head:	Specialized hydraulic powered system with drifter, feed advance, indexing control and rotation head that can drill holes, insert and tighten bolts
Handheld bolter:	Pneumatic rockdrill attached to a parallel telescopic jack leg that provides the feed force for vertical drilling