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### Managing Geotechnical Risk through Non-Destructive Rock Reinforcement Testing Trialled at the George Fisher Mine, Mt. Isa.

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# Managing Geotechnical Risk through Non-Destructive Rock Reinforcement Testing Trialled at the George Fisher Mine, Mt. Isa.

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## ABSTRACT

Corrosion affects the performance of rock support and reinforcement at various underground mines, including the George Fisher Mine, where recent studies showed that this risk to mining operations is generally not well understood. Corrosion reduces the capacity and life expectancy of ground support and generally is undetected unless the traditional destructive pull out test is employed to detect defect bolts. Where it is still acknowledged that the pull out test has still an important role to play in determining critical bond lengths for static and quasi static ground support designs, it does not provide an underground operation with any reassurance regarding its bolt's integrity, which has been compromised by in-situ aggressive conditions. Non-destructive rock reinforcement calibration testing on single and twin strand cable bolts, rebar bolts and friction bolts at the George Fisher Mine enabled the testing team to detect bolts with compromised integrity in one area of the mine. The non-destructive rock reinforcement integrity testing conducted uses a complex "Stress Wave Analysis" package based on the processing of clear seismic signals imparted into the *rock reinforcement element that* is being tested. The seismic signals are processed by "*Fourier Transform*" into various criteria which can be used to produce models of the element such as mechanical admittance, frequency spectra and velocity which are all being used in the final modelling of the rock reinforcement element under analysis. This paper highlights the enormous potential to effectively manage the geotechnical risk that corrosion presents for an underground mining operation.

## INTRODUCTION

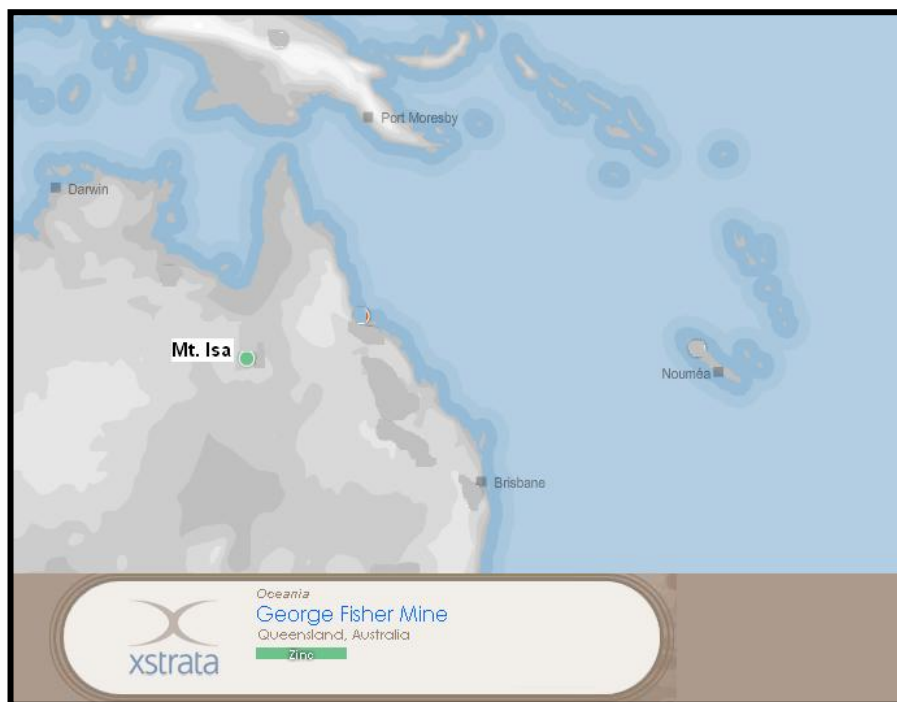
It has been found through previous studies that corrosion reduces the capacity and life expectancy of ground support (Villaescusa, Hassle and Thompson, 2007) and generally is undetected unless the traditional destructive pull out test (see Figure 1) is employed to detect defect bolts.



Fig 1 – Hydraulic Pull testing device used at the George Fisher Mine.

If the ground support elements do not fail after employing the pull testing device the uncertainty in regard the ground support system integrity remain. It was also apparent that the hydraulic pull testing device cannot provide a good indication of the effectiveness of the fully grouted bolt following a recent review of non-destructive testing (Buys, 2008). It is however acknowledged that the pull out test has still an important role to play in determining critical bond lengths for static and quasi static ground support designs but does not provide an underground operation with any reassurance regarding its bolt's integrity, which could have been compromised by in-situ aggressive conditions. Thus in order to determine whether ground support elements have been compromised through corrosion an operation would need to undergo destructive over coring of their rock reinforcement system. Not only is it an extremely time consuming exercise but quite expensive too.

The George Fisher Mine, which is located 20km north of Mt. Isa and over 950 km west of Townsville in North Queensland (See Figure 2), embarked on a program of Non-Destructive rock reinforcement calibration testing on single and twin strand cable bolts, rebar bolts and friction bolts which enabled the testing team to detect bolts with compromised integrity in one area of the mine. This testing program highlighted the enormous potential to effectively manage the geotechnical risk that corrosion presents for underground mining operations.



**Fig 2 – George Fisher Lead-Zinc Mine (2009 – XSTRATA Operations).**

## **BACKGROUND TO NON-DESTRUCTIVE TESTING**

Investigations into premature rock bolt failures in the Australian Coal Mining industry identified the problem in 9 different collieries throughout NSW and Queensland. Samples of broken bolts have been collected from at least 5 of these mines for detailed metallurgical testing. Because of the sporadic occurrence of premature bolt failure and the low level of record keeping within the mines, only a limited sample was available for the investigator's database. The investigation also highlighted that only bolts which have fallen to the ground are normally recognised as premature failures and to date there has been no method of identifying broken bolts which have failed within the encapsulated portion of the bolt or are restrained in the roof by strata shear. The

investigation recognised from the outset that the database obtained from broken bolts found on the floor of mine roadways may only be a small part of the problem. The type of failures being identified could just as easily be occurring within the grouted horizon. This would leave partially or totally failed bolts grouted into the roof, providing the potential for an extremely hazardous situation of roof instability developing, with little or no warning to operators. It was recognised that there was a need for a non-destructive device to be available to the industry to be able to check bolt integrity on a routine basis (Hebblewhite, Fabjanczyk and Gray, 2003).

Buy's (2008) found that studies to develop non-destructive testing methods to determine a rock bolt's integrity have been conducted since 1977. He further critically reviewed current developed systems and highlighted their respective limitations.

**(i) Boltometer**

Instrument can be used on cemented grouted bolts and also on polyester and some other grouts. Buy's found that the Boltometer can indicate bad ground, but if the impedance between the grout and surrounding rock are the same; wave energy will dissipate into the rock before it could reach a major defect, reporting good grouting.

**(ii) JK rockbolt tester**

Device developed by the JKMRRC at the University of Queensland and is based on the measurement and analysis of the complete dynamic response of the bolt. The essence of the method is to measure the frequency response function of the bolt. This function can be considered as the signature of the bolt in situ. Resonant frequencies and associated damping ratios are primarily determined by the mechanical characteristics of the bolt in situ, resin grout and the rock.

**(iii) GRANIT**

The ground anchorage integrity testing (GRANIT) system was developed at the University of Aberdeen in Scotland. This testing system applies an impulse of known force by means of an impact device that is attached to the tendons. The vibration signals that arise from this impulse are complex in nature and require analysis to be performed. Novel artificial intelligence techniques are used in order to learn the complicated relationships that exist between anchorage and its response to an impulse. A single axial impulse load is generated at the head of the tendon. A set of datum responses signatures for different post-tension levels is recorded for the anchorage immediately after installation. The condition of the tendon at any later date can be determined by comparing the datum with the characteristics of the subsequent response signatures. A change in characteristics indicates a potential change in the integrity of the anchorage. It is difficult determining the relationship between the dynamic response of the anchorage and its post tension level. Therefore, neural networks are implemented, which suit the task of learning such complicated non-linear relationships. The neural network, trained on a single tendon, may be used to diagnose the post tension level of a number of tendons. The disadvantage of this system is that it can only work on rock bolts that have been characterised at installation.

**(iv) Ultrasonic Guide Wave Testing**

A technique developed by Imperial College in England and it's based on an ultrasonic pulse echo test carried out from the free end of the bolt. Beard and Lowe (2003) showed that the approach could determine the bolt length and identify major defects such as loss of resin encapsulation, necking and deformation. A short duration Gaussian windowed sine burst is used to excite a guide wave in the bolt, which is then reflected from the bolt end and from any major defects. The reason for using a Gaussian windowed sine burst signal is that the excitation frequency can be tightly controlled and thereby excites specific modes. From the reflection arrival time and knowledge of the wave velocity dispersion curves the positions of the defects or the bolt length can be calculated. The maximum test range is limited by the amount of attenuation that the wave experiences as it propagates. The major cause of attenuation is the fact that ultrasonic energy tends to leak from the bolt into the surrounding rock. The study concluded that bolts should be tested in its low frequency range (30-70 kHz) as well as in its high frequency range (2-5 MHz). The low frequency test can be used to identify defects such as partial bolt encapsulation and possibly corrosion patches near the bolt surface. The high frequency test is not sensitive to surface defects, but can give a reliable indication of the bolt length. It was not possible with their modeling tools to determine the dispersion relationships for

bars with 3 dimensional features, as the rock bolt end and certain defects are not always axial symmetric it may be necessary to model the bolt with three-dimensional finite element methods.

The MODSHOCK system used within the testing program at the George Fischer mine compared to the above methods is relatively simple in operation. In simple terms, the modified shock test as described by Higgs and Tongue (1999) is a seismic test using a hammer blow as the force and a transducer to pick up the resultant vibrations. With the application of digital filtering techniques an accurate mechanical admittance vs. frequency plot is obtained which can then be interpreted using the concepts developed by Davis & Dunn (1974).

This non-destructive method by vibration has its origins from Davis and Dunn where they carried out various types of non-destructive pile tests on sites in Western Europe and other French speaking countries for “*The Centre Experimental de Recherches et d’Etudes du Batiment et des Travaux Publics*” (CEBTP) of France. This vibration method had also been used and described by Gardner and Moses (1973), but this technique had not been exploited by British engineers to the extent that could have been useful to them because of a lack of knowledge of the technique and a degree of mysticism associated with the interpretation of the results.

Since vibration testing of piles was first started by the CEBTP a considerable amount of theoretical work had been done which shed light on interpretation, and the experience of testing many thousands of piles led to the technique being applied with more confidence to piles on sites which lend themselves to being tested in this way. The main function of the test was to detect any major defect such as an open fracture or an important strangulation of the concrete, particularly in the upper portion of the pile.

The method is based on measuring the frequency and amplitude response of a rock reinforcement element known as impulse. This response, known as Mechanical Admittance (or mobility), contains all the information necessary to confirm rock reinforcement integrity and to analyse the surrounding influences. At higher frequencies the resonating harmonics of the rock reinforcement element are detected, whereas at low frequency the response is generally linear allowing measurement of the element-head stiffness.

The non-destructive rock reinforcement integrity testing analysis is conducted using a complex “Stress Wave Analysis” package based on the processing of clear seismic signals imparted into the *rock reinforcement element that* is being tested. The seismic signals are processed by “*Fourier Transform*” into various criteria which can be used to produce models of the element such as mechanical admittance, frequency spectra and velocity which are all being used in the final modelling of the rock reinforcement element under analysis.

In research and laboratory applications of modal analysis, particularly of complex machinery, dynamic excitation was often provided by a linear hydraulic or eccentric mass shaker. Experience gained in testing over 140 bridges indicated that simpler means of excitation are suitable for 90% of all bridges where attaching shakers to bridges were seen as a complex and costly method and is only practical for research purposes or for extremely complex structures [4]. Similarly the application for rock reinforcement integrity testing it was found that a simpler method to excite bolts is adequate for the detection of defects.

The development of the Australian based testing method started in the late 80’s and has been used for the correct assessment on a large variety of elements, which now exceeds well over 1,000,000 tests for more than 20 years [5]. Integrity Testing PTY LTD (i.e. developers of the Modshock system) has for over 15 years carried out testing of long length steel rods, either as strand or solid steel bars. The most notable project was for BHP, when they owned the Whyalla steel works where they tested the tie rods holding back the crucial steel pile wall of the coal handling jetty.

The rods were tested and not only were the defective rods identified but it was indicated at what point the rods had lost a large cross section. This was located at a point where the rods came close to the base of the coal handling pit and water was seeping onto the rods causing corrosion. Thus a large successful background in the testing of steel embedded elements, generally with the lengths in excess of 5 meters.

# CALIBRATION TESTING PROGRAM AT GEORGE FISHER MINE

The bolts tested at George Fisher Lead-Zinc Mine consisted of:

- i) **Cable Bolts**
- ii) **Resin Bolts and**
- iii) **Friction Stabiliser Bolts.**

## i) Cable Bolts

The cable bolts tested were:

- 6m and 8m Single Strand Cable Bolts – One bulb per meter.
- 6m and 8m Twin Strand Cable Bolts - One bulb per meter.



Fig 3 – Cable Bolt Diagram.

Table 1 – Mechanical Properties for 15.2mm diameter Cable Bolt.

Mechanical Properties		
	Minimum	Typical
Core Diameter - unbulbed section (mm)	-	15.2
Cross Sectional Area - unbulbed section (sq.mm)	-	143
Yield Force - 0.2% (kN)	212	235
Tensile Force (kN)	250	265
Elongation on 600mm length (%)	3.5	6.5
Mass per metre - Bar (kg/m)	-	1.125

## ii) Resin Bolts

The resin bolts tested were:

- 2.2m Thread Bar Posimix.

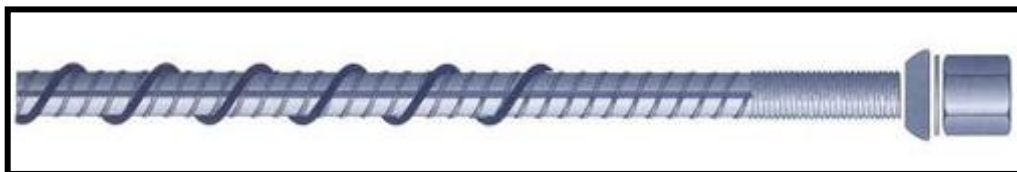


Fig 4 – Thread Bar Posimix.

**Table 2 – Mechanical Properties for Thread bar Posimix.**

Thread Bar Posimix Physical Properties	Minimum		Typical	
	Yield Strength	500MPa	160kN	550MPa
Ultimate Tensile Strength of Tube	600MPa	185kN	650MPa	200kN
Calculated Shear Strength	120kN		130kN	
Standard Elongation	16%		19%	
Uniform Elongation			12%	
Mass Per Metre			2.47kg	
Bar Core Diameter			20.0mm	
Cross Sectional Area of Bar			310mm <sup>2</sup>	
Major Bar Diameter			22.1mm max.	
Bar Straightness to AS 1442-1991				

**iii) Friction Bolts**

The friction bolts tested were:

- 2.4m Friction Bolt, 47mm diameter.



**Fig 5 – Friction Bolt 47mm diameter diagram.**

**Table 3 – Mechanical Properties for the Friction Bolt.**

47mm Friction Bolt Physical Properties	Minimum		Typical	
Yield Strength	345MPa	120kN	445MPa	160kN
Ultimate Tensile Strength of Tube	460MPa	165kN	510MPa	180kN
Friction Bolt Diameter	47mm			
Rec.Hole Diameter Range	43mm min / 45.5mm max.			
Mass Per Metre			2.79 kg	

**Test Site Locations**

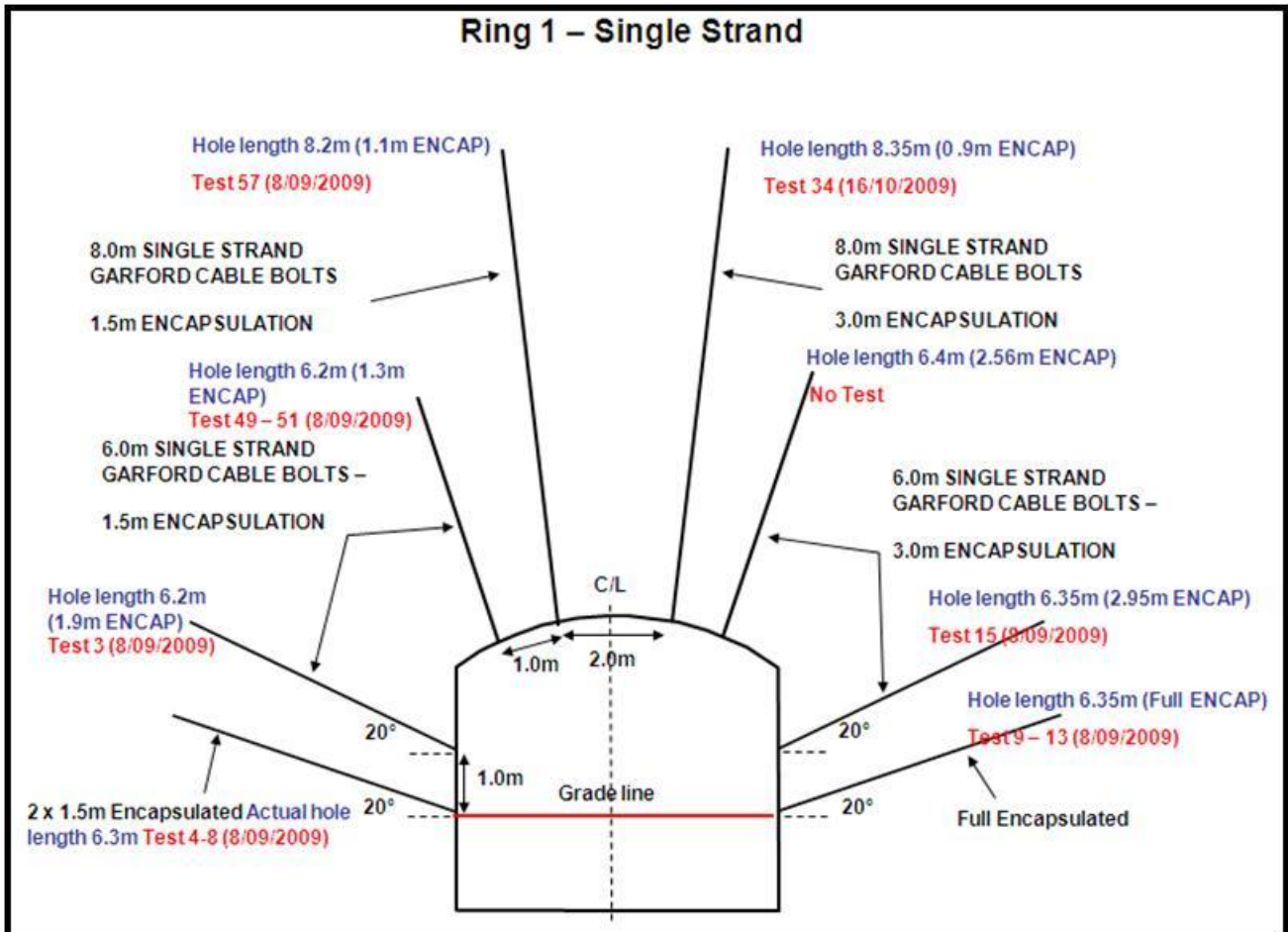
The site testing was conducted on the 8<sup>th</sup> September 2009 and 16<sup>th</sup> October 2009. The following site were selected by Mr. Fred Harvey (Rock Mechanics Superintendent):

- 6 Level 5053 EXC – Calibration Tests for Cable Bolts, Resin bolts and Friction Bolts.
- 16 Level – Tests for grouted and resin solid bars (Test results not part of this paper).

## 6 Level 5053 East Crosscut Calibration Tests

**Table 4 – Single Strand Cable Bolts Calibration Set-up.**

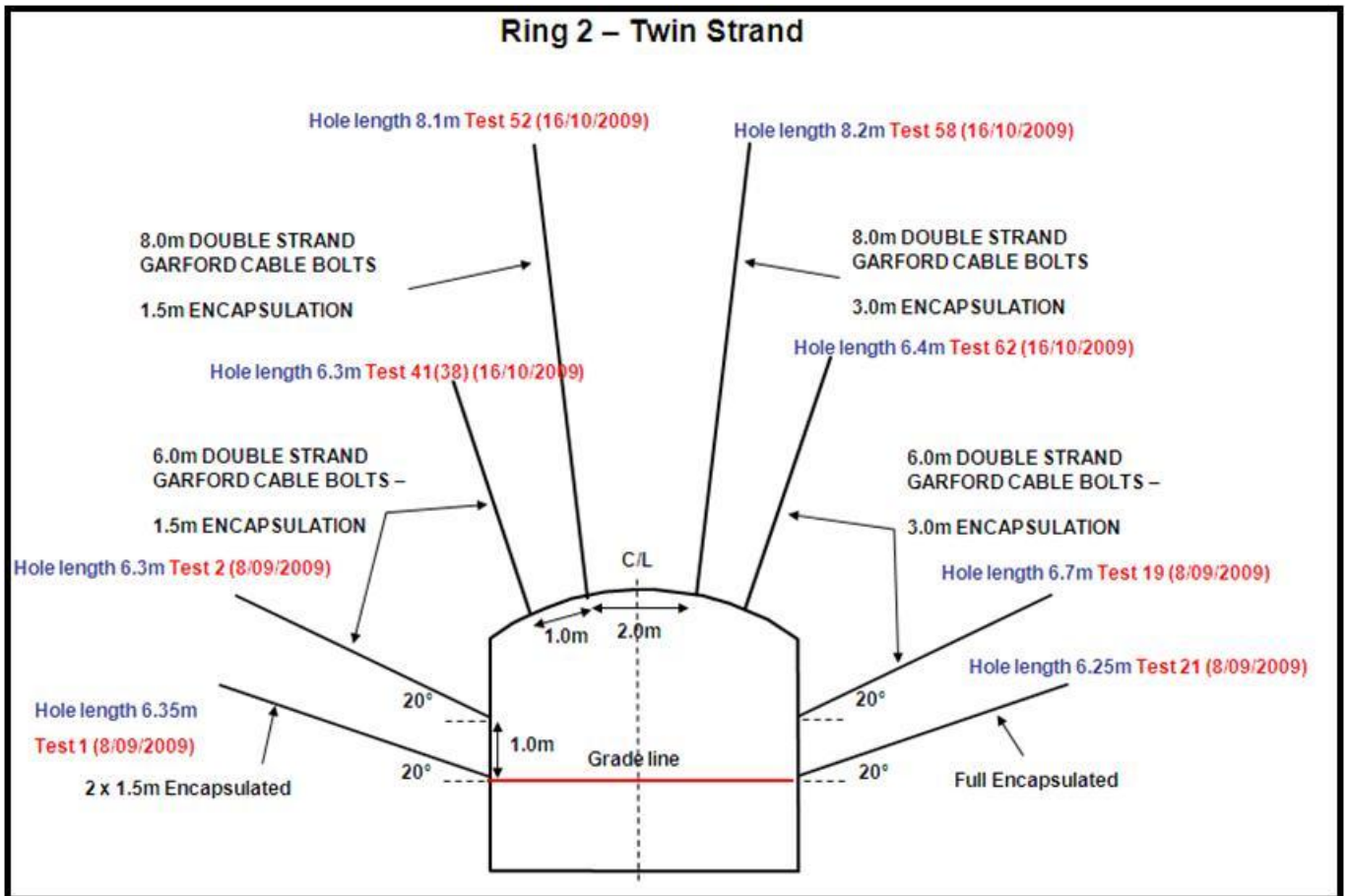
Bolt Test No.	Test Date	Hole Length	Hole Angle	Comments
4 (8)	8 <sup>th</sup> Sept. '09	6.3m	20 deg (Sidewall)	1.5m encapsulation at the toe and collar
3	8 <sup>th</sup> Sept. '09	6.2m	20 deg (Sidewall)	1.9m encapsulation at the toe
49 (51)	8 <sup>th</sup> Sept. '09	6.2m	75 deg (Backs)	1.9m (1.5m) encapsulation at the toe
57	8 <sup>th</sup> Sept. '09	8.2m	75 deg (Backs)	1.1m encapsulation at the toe
34	16 <sup>th</sup> Oct. '09	8.35m	75 deg (Backs)	0.9m encapsulation at the toe
15	8 <sup>th</sup> Sept. '09	6.35m	20 deg (Sidewall)	2.95m encapsulation at the toe
9 (13)	8 <sup>th</sup> Sept. '09	6.35m	20 deg (Sidewall)	Full encapsulation



**Fig 6 – Schematic illustrating single strand cable bolt calibration set-up.**

**Table 5 – Twin Strand Cable Bolts Calibration Set-up.**

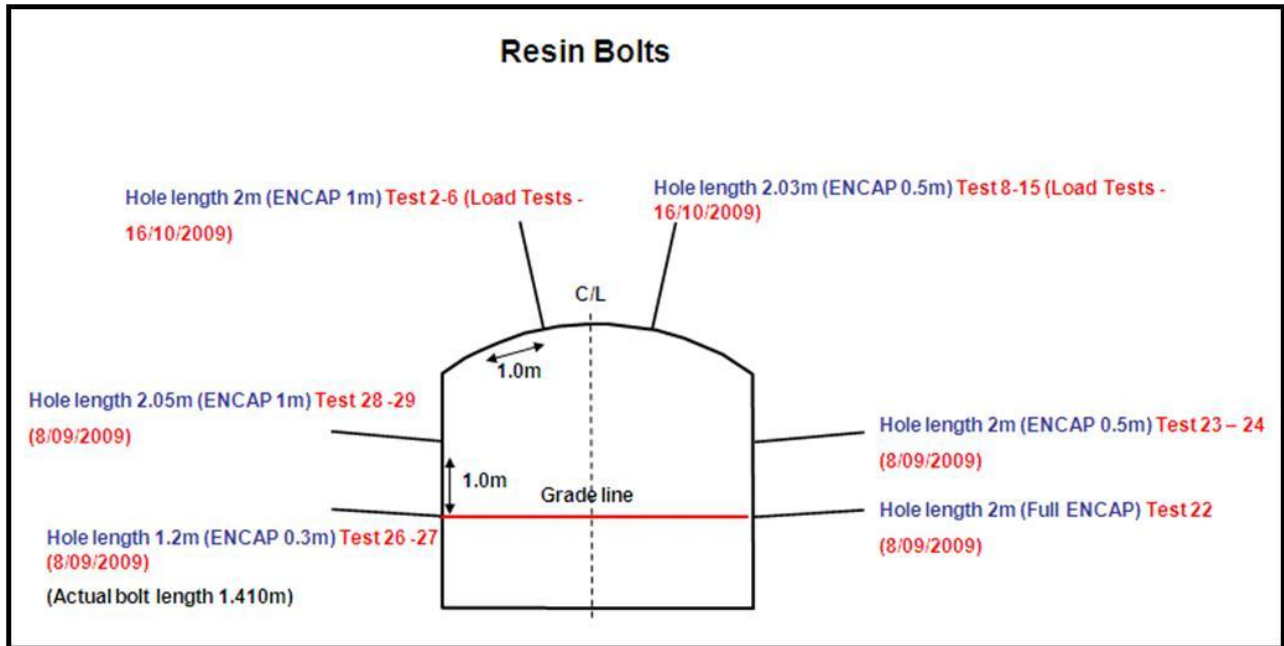
Bolt Test No.	Test Date	Hole Length	Hole Angle	Comments
1	8 <sup>th</sup> Sept. '09	6.35m	20 deg (Sidewall)	1.5m encapsulation at the toe and collar
2	8 <sup>th</sup> Sept. '09	6.3m	20 deg (Sidewall)	1.5m encapsulation at the toe
41 (38)	16 <sup>th</sup> Oct. '09	6.3m	75 deg (Backs)	1.5m encapsulation at the toe
52	16 <sup>th</sup> Oct. '09	8.1m	75 deg (Backs)	1.5m encapsulation at the toe
58	16 <sup>th</sup> Oct. '09	8.2m	75 deg (Backs)	3.0m encapsulation at the toe
62	16 <sup>th</sup> Oct. '09	6.4m	75 deg (Backs)	3.0m encapsulation at the toe
19	8 <sup>th</sup> Sept. '09	6.7m	20 deg (Sidewall)	3.0m encapsulation at the toe
21	8 <sup>th</sup> Sept. '09	6.25m	20 deg (Sidewall)	Full encapsulation



**Fig 7 – Schematic illustrating twin strand cable bolt calibration set-up.**

**Table 6 – Resin Bolt Calibration Set-up.**

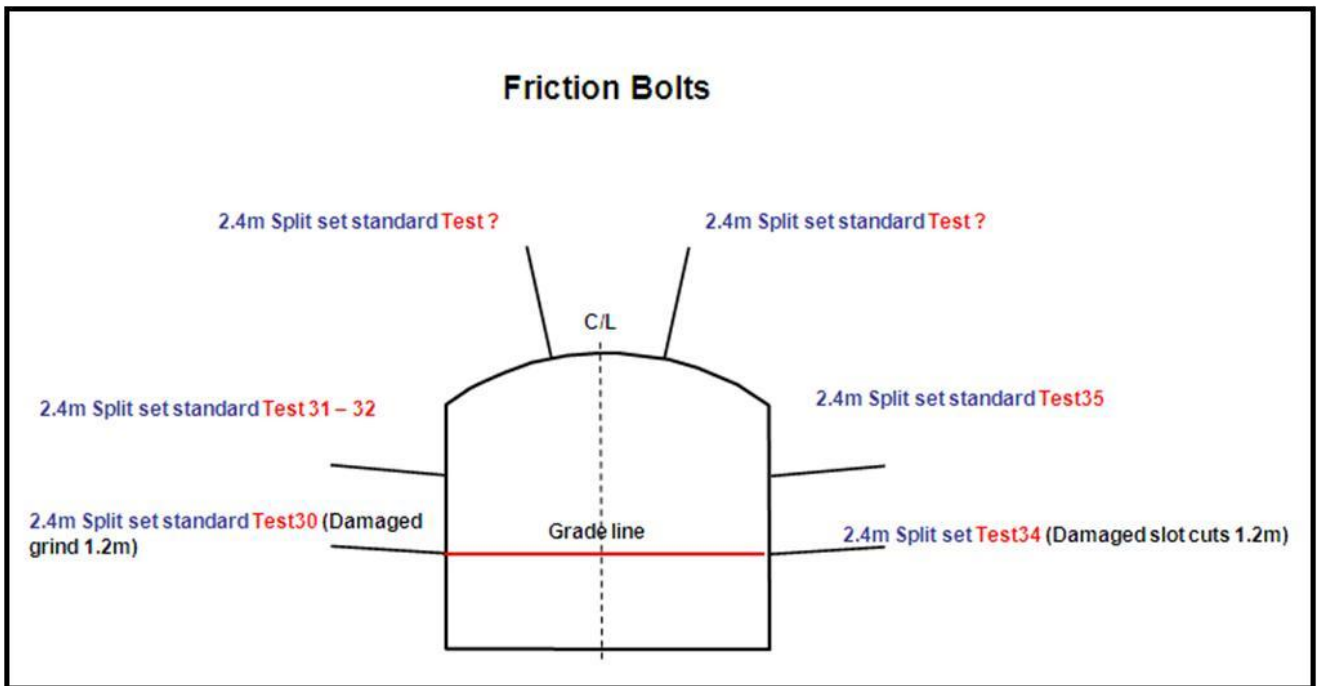
Bolt Test No.	Test Date	Hole Length	Hole Angle	Comments
26(27)	8 <sup>th</sup> Sept. '09	1.2m (Actual bolt Length 1.4m)	20 deg (Sidewall)	0.3m encapsulation at the toe
28(29)	8 <sup>th</sup> Sept. '09	2.05m	20 deg (Sidewall)	1.0m encapsulation at the toe
2-6	16 <sup>th</sup> Oct. '09	2.0m	75 deg (Backs)	1.0m encapsulation at the toe – Pull Testing conducted at 4, 6, 10 and 12.5 tonnes
9 - 15	16 <sup>th</sup> Oct. '09	2.03m	75 deg (Backs)	0.5m encapsulation at the toe - Pull Testing conducted at 4, 6, 8, 10 and 12.5 tonnes
23(24)	8 <sup>th</sup> Sept. '09	2.0m	20 deg (Sidewall)	0.5m encapsulation at the toe
22	8 <sup>th</sup> Sept. '09	2.0m	20 deg (Sidewall)	Full encapsulation



**Fig 8 – Schematic illustrating resin bolts calibration set-up.**

**Table 7 – Friction Bolts Calibration Set-up.**

Bolt Test No.	Test Date	Hole Length	Hole Angle	Comments
30	8 <sup>th</sup> Sept. '09	2.4m	20 deg (Sidewall)	Standard installation (Damaged grind at 1.2m)
31 (32)	8 <sup>th</sup> Sept. '09	2.4m	20 deg (Sidewall)	Standard installation
35	8 <sup>th</sup> Sept. '09	2.4m	20 deg (Sidewall)	Standard installation
34	8 <sup>th</sup> Sept. '09	2.4m	20 deg (Sidewall)	Standard installation (Damaged slots cut at 1.2m)



**Fig 9 – Schematic illustrating resin bolts calibration set-up.**

## 16 Level Tests

Four tests areas were selected:

- Test Area 1 - Northern shaft bypass excavation
- Test Area 2 - Old Crib Room
- Test Area 3 – Opposite Sub Station
- Test Area 4 – Opposite temporary crib room

16 Level were chosen in particular as the area is subject to very aggressive corrosive conditions. Test Area 2 (Old Crib Room) rock bolts exhibits a high level of corrosion and evidence of this was found in a rock bolt that dislodged from the backs (see Figure 10 - corroded rockbolt).



**Fig 10 – Corroded bolt, 16 level crib room.**

## **TESTS**

A total of 56 bolts were tested between the 8<sup>th</sup> September and 16<sup>th</sup> October 2009 (19 bolts on the 8<sup>th</sup> September '09 and 37 bolts on the 16<sup>th</sup> October '09). The data obtained were transferred from the field Notebook PC of the Mod-Shock System and analysed with the IntegxD7 Programme (Integrity Testing Pty Ltd). Slight modifications (i.e. Graph presentation) to the programme's output graphs were made during the analysis process. These changes were necessary to provide George Fisher Lead-Zinc Mine with clear results.

## **TEST RESULTS AND DISCUSSIONS**

### **Calibration Bolts – 6 Level 5053**

#### **Single Strand Cable Bolts**

During our investigation (calibration testing) on the cable bolts we noticed an interesting phenomenon in the 2D mechanical admittance plot for the cable bolts which were previously noticed when testing cable bolts at another mine. This relates to the first part of the mechanical admittance plot (see below Figure 11 – Single Strand Cable Bolt Test No.4).

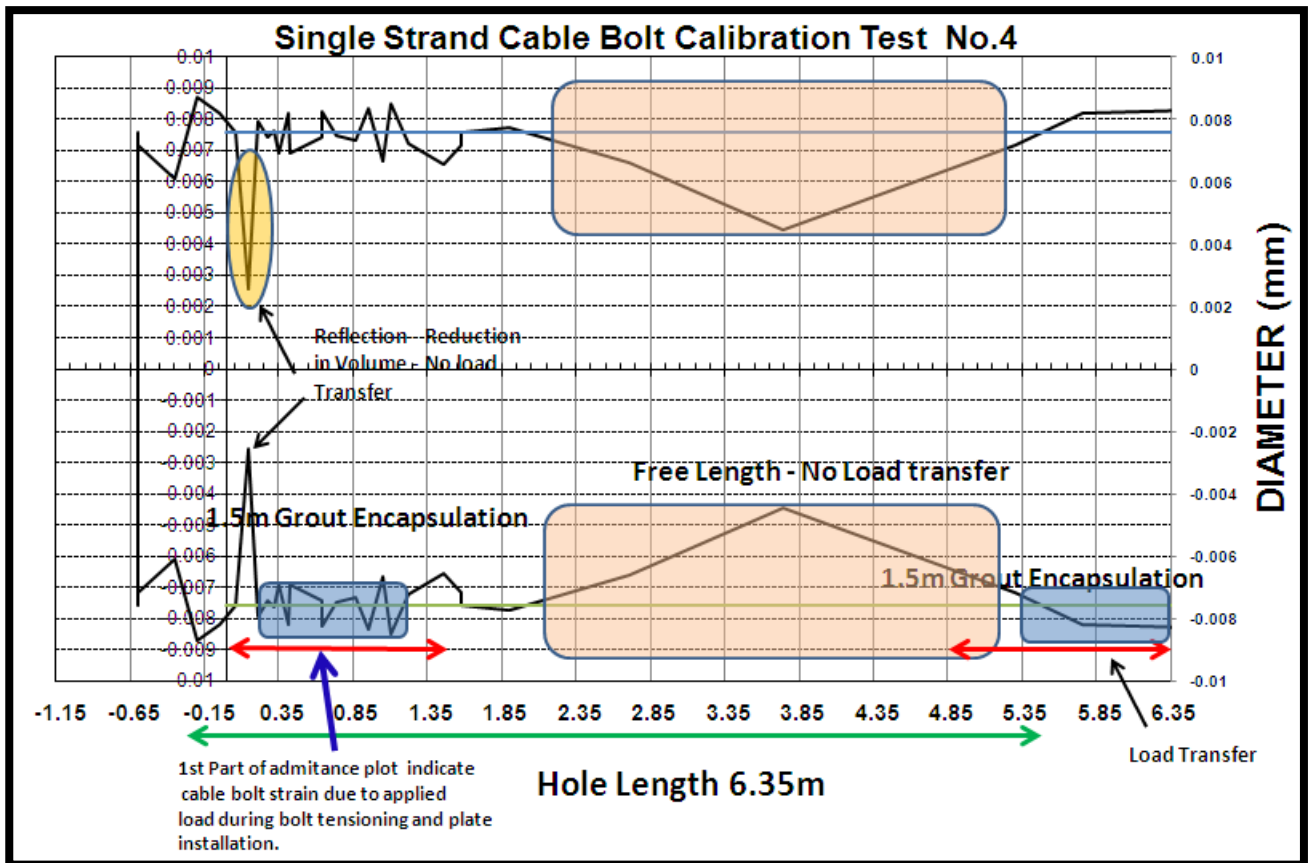
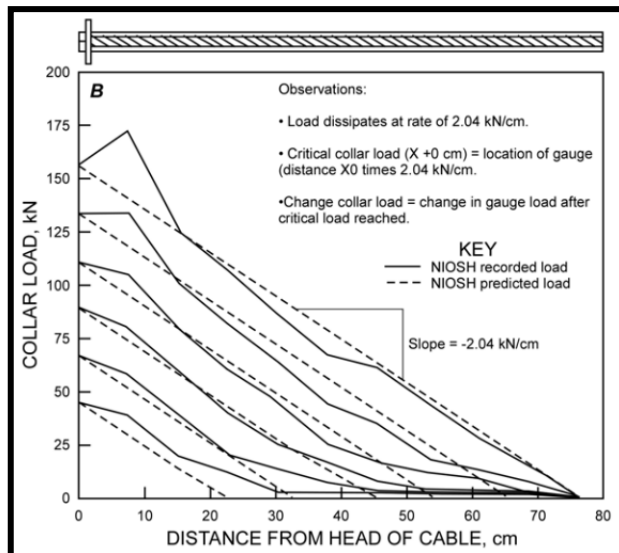


Fig 11 - 2D Plot for Single Strand Cable Test No.4.

The above graph shows some similarity to the load vs dissipation rate graph of a fairly recent (2004) collaborative investigation into the behaviour of cable bolts between the University of Saskatchewan, Saskatoon; Itasca Consulting Group, Inc., Minneapolis; University of British Columbia, Vancouver (BC) and the US National Institute of Safety and Health (NIOSH), which provided valuable information regarding their loading and strain behaviour.

An article by Martin et al (2004) showed that a critical load is required before the cable bolt, at a given location, sense any load. This was done through instrumented cable bolts loaded at the collar and plotted against recorded microstrain at individual gauge locations (see below in Figure 12 the load profile along the length of the cable at different collar loads). This implied that a gauge positioned 25.4 cm from the collar will sense load only when the collar load exceeds  $25.4 \times 2,043 \text{ N/cm}$ .



**Fig 12 – Collar load plotted against A, microstrain (load profile curve) and B, distance from head of cable (load correlation curve, Martin et al (2004)).**

The above phenomenon however would need to be confirmed with some instrumented bolts.

The test results obtained from the calibration tests are discussed below.

**Table 8 – Single Strand Cable Bolts test result summary.**

Test	Element Test Number	Bolt Type	Location	Nominal Length of Element (m)	Bar Stiffness (t/mm)	"E" max (t/mm)	"E" min (t/mm)
<a href="#">MCAB3</a>	3	Single strand Cable Bolt	6 Level 5053	7.0	2.2	1.5	0.9
<a href="#">MCAB 4</a>	4	Single strand Cable Bolt	6 Level 5053	7.0	1.3	1.6	1.1
<a href="#">MCAB 8</a>	8	Single strand Cable Bolt	6 Level 5053	7.0	0.8	2.2	1.0
<a href="#">MCAB 9</a>	9	Single strand Cable Bolt	6 Level 5053	7.0	0.9	2.1	1.2
<a href="#">MCAB 10</a>	10	Single strand Cable Bolt	6 Level 5053	7.0	1.5	2.6	0.8
<a href="#">MCAB 13</a>	13	Single strand Cable Bolt	6 Level 5053	7.0	0.9	1.8	1.0
<a href="#">MCAB 15</a>	15	Single strand Cable Bolt	6 Level 5053	7.0	0.5	2.0	1.1
<a href="#">MCAB34</a>	34	Single strand Cable Bolt	6 Level 5053	8.6	0.4	1.8	0.9
<a href="#">MCAB 49</a>	49	Single strand Cable Bolt	6 Level 5053	7.0	0.5	1.8	0.8
<a href="#">MCAB 51</a>	51	Single strand Cable Bolt	6 Level 5053	7.0	0.2	2.5	1.0
<a href="#">MCAB 57</a>	57	Single strand Cable Bolt	6 Level 5053	7.0	6.4	2.3	1.0

The following comments were made regarding the calibration tests for the single strand cable tests data interpretation:

- Tests 4 and 8 were done on the same bolt. The test results showed that the grouting of the toe and collar with a centre free length was clearly detected using the Modshock system. The anticipated grout location of 1.5m away from the toe and collar could not be accurately

picked as the location of the grout appears to be slightly different that what has been proposed. This could very well be a sign of the lack of control during the grout installation.

- Test 3 results showed that the grouting of the toe (1.9m) and free length towards the collar was clearly detected using the Modshock system. The 6.0m long cable had a 0.692m tail and 5.31m length inside the hole. The anticipated grout embedment length of 1.9m has been detected (i.e. an area of load transfer) and appear to be located at 3.6m to 5.5m. The test result also suggests a gap towards the end of the hole (see Figure 13).

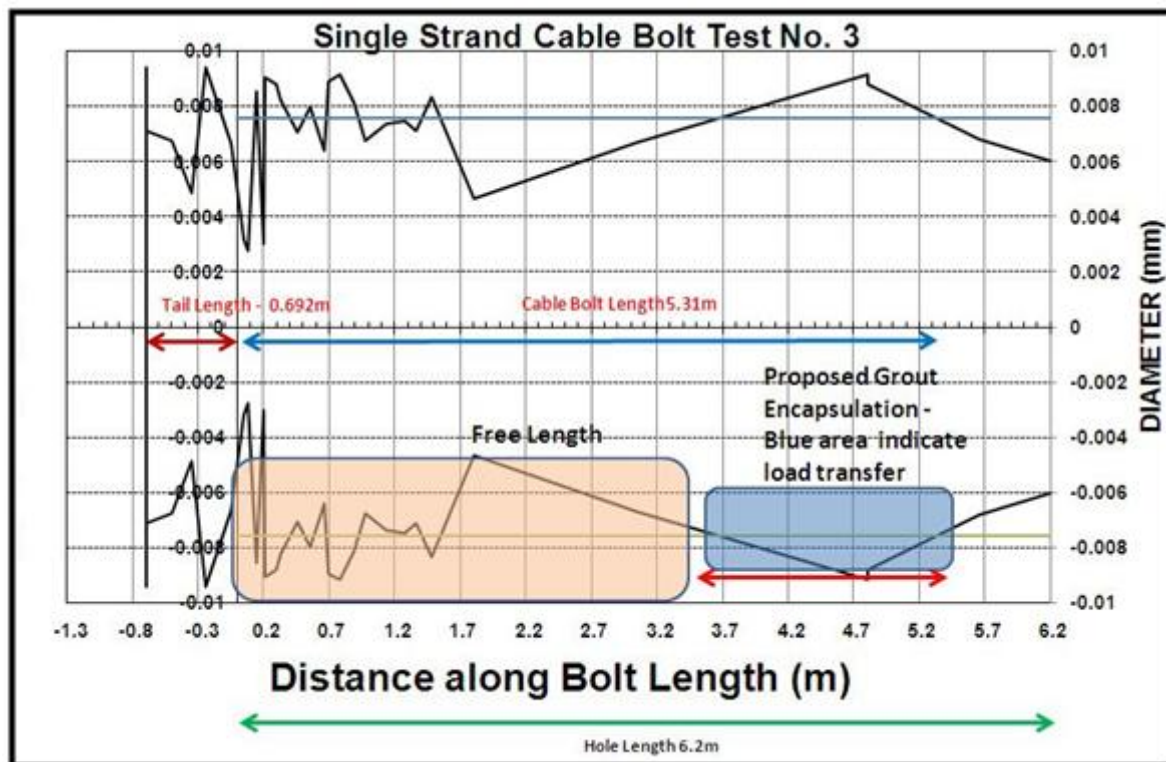
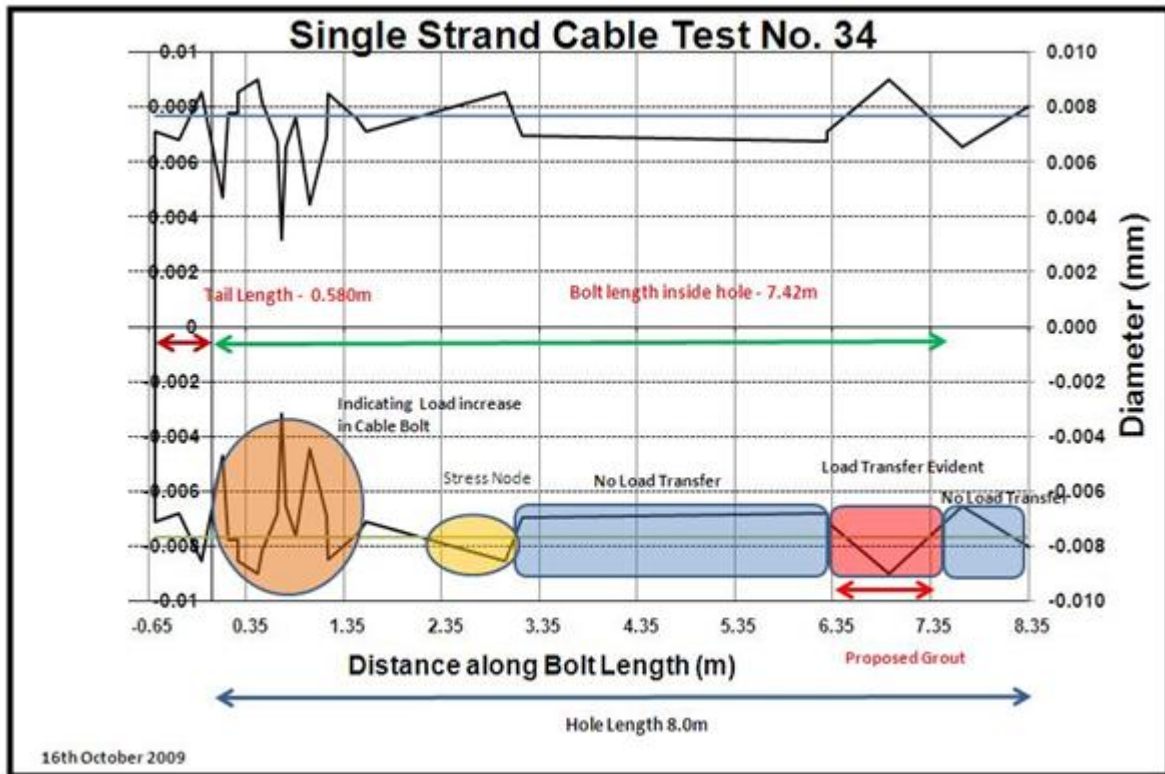


Fig 13 - 2D Plot for Single Strand Cable Test No.3.

- Test 51 showed that the grout location appear to be between 2.7m and 4.4m an embedment length of 1.7m and not the anticipated 1.3m grouted length. The cable bolt had a tail length 0.402m and 5.598m length inside the 6.2m long hole. This would be one of the cable bolts required to be checked for correct embedment length.
- Test No 34 showed that the grouting of the cable bolt toe (0.9m) and free length towards the collar was clearly detected using the Modshock system. The 8.0m long cable had a 0.402m tail and 7.42m length inside the hole. The anticipated grout embedment length of 0.9m has been detected (i.e. an area of load transfer) and appear to be located at 6.35m to 7.35m. The test result also suggests a gap towards the end of the hole (see Figure 14).



**Fig 14 - 2D Plot for Single Strand Cable Test No.34.**

- Test No 57 – Very poor signal – Test discarded.
- Test No 15 showed that the grouting of the cable bolt toe (2.95m) and free length towards the collar was clearly detected using the Modshock system. The 6.0m long cable had a 0.500m tail and 5.5m length inside the hole. The anticipated grout embedment length of 2.95m has been detected (i.e. an area of load transfer) and appear to be located at 3.4m to 5.85m. The test result also suggests a gap towards the end of the hole.
- Test No 13 and 9 showed that full column grouting of the hole did not occur as load transfer for both tests appear to be towards the latter part of the hole and a gap towards the earlier parts of the hole.

### **Twin Strand Cable Bolts**

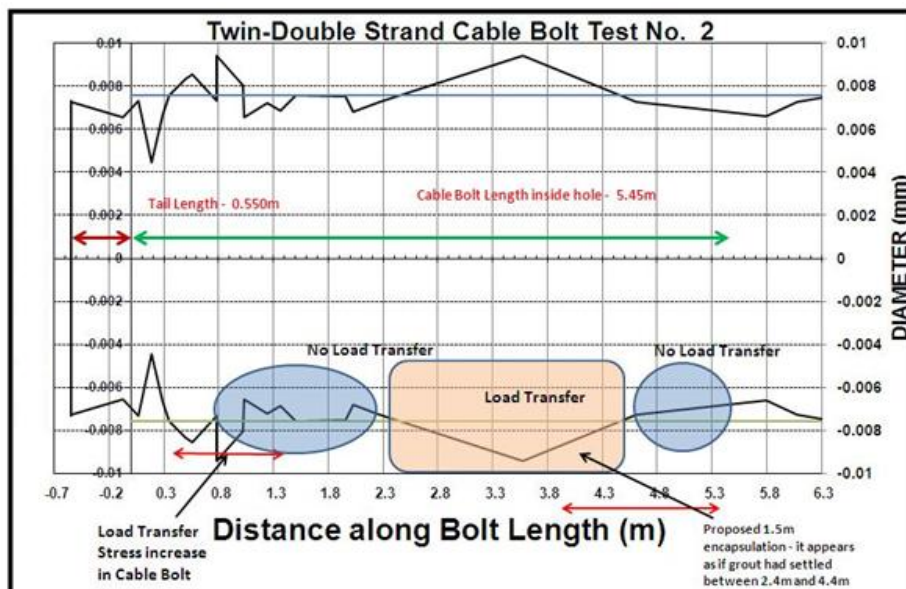
The test results obtained from the calibration tests are discussed below. A summary of the test results are provided below in Table 9.

**Table 9 – Twin Strand Cable Bolts test result summary.**

Test	Element Test Number	Bolt Type	Location	Nominal Length of Element (m)	Bar Stiffness (t/mm)	"E" max (t/mm)	"E" min (t/mm)
<a href="#">MCAB 1</a>	1	Twin Strand Cable Bolt	6 Level 5053	7.0	0.5	2.0	1.1
<a href="#">MCAB 2</a>	2	Twin Strand Cable Bolt	6 Level 5053	7.0	2.2	1.9	0.8
<a href="#">MCAB 19</a>	19	Twin Strand Cable Bolt	6 Level 5053	7.0	0.4	1.6	0.7
<a href="#">MCAB 21</a>	21	Twin Strand Cable Bolt	6 Level 5053	6.3	1.4	1.6	0.7
<a href="#">MCAB 52</a>	52	Twin Strand Cable Bolt	6 Level 5053	8.6	1.1	1.6	0.6
<a href="#">MCAB 58</a>	58	Twin Strand Cable Bolt	6 Level 5053	8.6	0.5	2.0	0.3
<a href="#">MCAB41</a>	41	Twin Strand Cable Bolt	6 Level 5053	8.6	0.7	2.2	1.0
<a href="#">MCAB62</a>	62	Twin Strand Cable Bolt	6 Level 5053	8.6	0.7	1.9	0.8

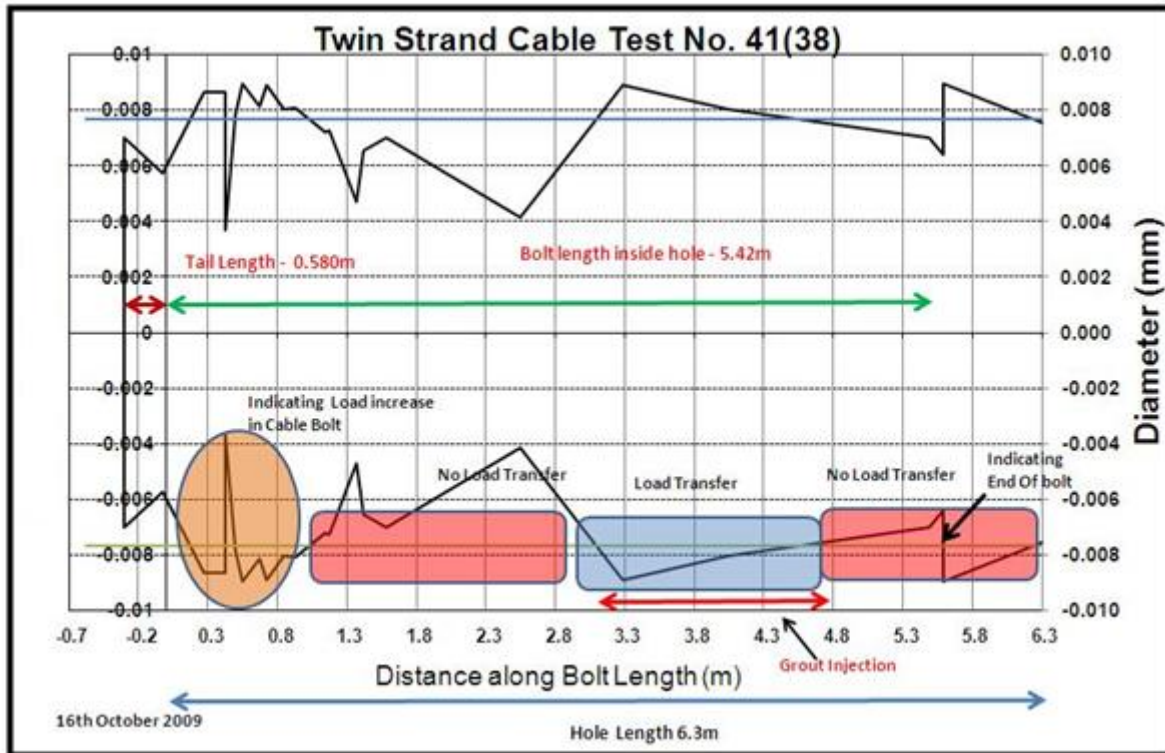
The following comments are made regarding the calibration tests for the twin strand cable tests data interpretation:

- Tests 1 results showed that the grouting of the toe and collar with a centre free length was clearly detected using the Modshock system. The anticipated grout location of 1.5m away from the toe and collar could not be accurately picked as the location of the grout appears to be slightly different that what has been proposed. The toe area only shows a 0.7m area embedment length with bolt end at 6.0m.
- Test 2 results showed that the grouting of the toe and free length towards the collar was clearly detected using the Modshock system. The 6.0m long cable had a 0.550m tail and 5.45m length inside the hole. The anticipated grout embedment length of 1.5m appears to cover a much larger area (i.e. 2.0m – 2.4 to 4.4m) than what was proposed (i.e. an area of load transfer). The test result also suggests a gap towards the end of the hole (see Figure 15).



**Fig 15 - 2D Plot for Twin Strand Cable Test No.2.**

- Test 41 results showed that the grouting towards the toe of the hole was clearly detected using the Modshock system. The 6.0m long cable had a 0.580m tail and 5.42m length inside the hole. The anticipated grout embedment length of 1.5m appears to covers a slightly larger area (i.e. 3.0m – 4.7m) than what was proposed (i.e. an area of load transfer). The test result also suggests a gap towards the end of the hole (See Figure 16).



**Fig 16 - 2D Plot for Twin Strand Cable Test No.41.**

- Test 52 results clearly shows the end of the bolt at 7.7m, but indicates that the grouting towards the toe of the hole only covered about 1m (i.e. between 6-7m). The 8.0m long cable had a 0.30m tail and 7.7m length inside the hole. The anticipated grout embedment length of 1.5m appears to covers a slightly smaller area (i.e. 6.0m – 7.0m) than what was proposed (i.e. an area of load transfer). The test result also suggests a gap towards the end of the hole.
- A test 58 result does not clearly show the end of the bolt at 7.36m and indicates that the grouting towards the toe of the hole covers about 1m (i.e. between 6.5-7.36m). The 8.0m long cable had a 0.640m tail and 7.36m length inside the hole. The anticipated grout embedment length of 3.0m appears to cover only a smaller area (i.e. 6.5m – 7.36m) than what was proposed (i.e. an area of load transfer). The test results indicate that grouting was done for a 1.7m distance to the back of the hole (i.e. 8.2m). The result also suggests remnant grout lower down the whole as an area of high load transfer is shown.
- A test 62 result does not clearly show the proposed end of the bolt at 5.7m. The results indicate that the grouting towards the toe of the hole covers about 1m (i.e. between 5.2m – 6.2m). The 6.0m long cable had a 0.30m tail and 5.7m length inside the hole. The anticipated grout embedment length of 3.0m appears to cover only a smaller area (i.e. 5.2m – 6.2m) than what was proposed (i.e. an area of load transfer). The result, similar to the previous test 58m, suggests remnant grout lower down the whole as an area of high load transfer is shown.

- Test 21 results clearly shows a full column grouted bolt with only one major reflection point within in the total length at 1.25m. The 2D mechanical admittance plot clearly indicates a full column grouted bolt with also similar stress / strain patterns closer to the collar of the hole. When testing cable bolts this is typical what the signature should show.

## Resin Bolts

The test results obtained from the calibration tests are discussed below. A summary of the test results are provided below in Table 10.

**Table 10 – Resin Bolts test result summary.**

Test	Element Test Number	Bolt Type	Location	Nominal Length of Element (m)	Bar Stiffness (t/mm)	"E" max (t/mm)	"E" min (t/mm)
<a href="#">MRES27</a>	27	Resin Bar	6 Level 5053	2.2	3.3	2.5	1.4
<a href="#">MRES29</a>	29	Resin Bar	6 Level 5053	2.2	2.3	3.4	1.8
<a href="#">MRES2</a>	2	Resin Bar	6 Level 5053	2.2	1.1	2.7	1.1
<a href="#">MRES3</a>	3	Resin Bar	6 Level 5053	2.2	3.3	3.2	1.6
<a href="#">MRES4</a>	4	Resin Bar	6 Level 5053	2.2	3.1	3.4	1.8
<a href="#">MRES5</a>	5	Resin Bar	6 Level 5053	2.2	2.1	3.9	1.6
<a href="#">MRES6</a>	6	Resin Bar	6 Level 5053	2.2	2.1	3.1	1.5
<a href="#">MRES 8</a>	8	Resin Bar	6 Level 5053	2.2	0.6	2.5	0.6
<a href="#">MRES9</a>	9	Resin Bar	6 Level 5053	2.2	1.0	3.3	1.7
<a href="#">MRES11</a>	11	Resin Bar	6 Level 5053	2.2	0.8	3.3	1.9
<a href="#">MRES12</a>	12	Resin Bar	6 Level 5053	2.2	2.3	4.1	2.4
<a href="#">MRES13</a>	13	Resin Bar	6 Level 5053	2.2	2.9	3.6	1.8
<a href="#">MRES15</a>	15	Resin Bar	6 Level 5053	2.2	3.9	3.6	1.6
<a href="#">MRES24</a>	24	Resin Bar	6 Level 5053	2.2	0.8	3.8	1.8
<a href="#">MRES22</a>	22	Resin Bar	6 Level 5053	2.2	1.9	3.3	1.7
<a href="#">MRES 1</a>	1 (22)	Resin Bar	6 Level 5053	2.2	1.4	3.0	1.8

The following comments are made regarding the calibration tests for the resin bolt tests data interpretation:

- Test 27 was a shorter bolt installed by George Fisher and following a detailed analysis of the bolt signal and admittance plot it shows clearly areas of load transfer and / or mechanical admittance. It is recognised that through the initial review the bolt appeared to be the full 2.2m length. However two significant reflection points showed a no load transfer or discontinued admittance in the 2D plot (see figure 17).



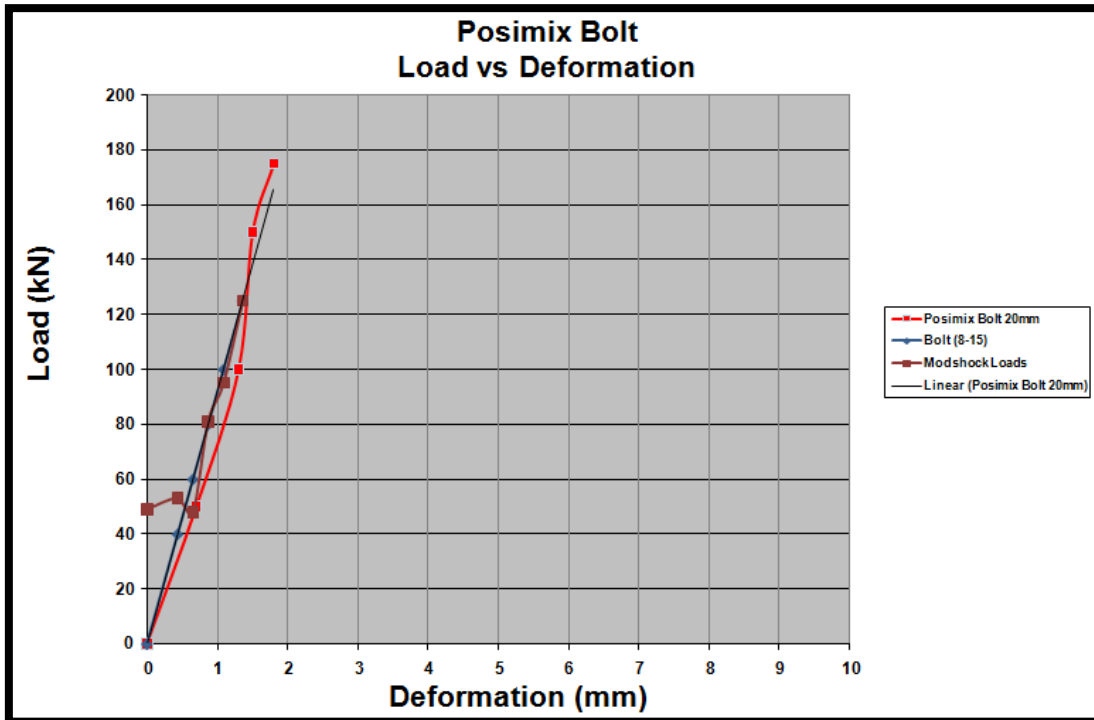


Fig 18 – Load vs Deformation graph for bolt test 8-15 (Modshock vs Pull Test Results).

- Test 24 was a 2.2m long bolt with a proposed 0.5m encapsulation at the toe of the hole. The 2D mechanical admittance plot however suggests the resin encapsulation and load transfer to be between 1.1m and 1.7m. We also noticed a reflection point in the early part of the mechanical admittance plot which suggests an increase in load due to the pre-loading during the installation. This however would require further confirmation through instrumented bolts.
- Test 22 was a 2.2m long bolt with a proposed full column encapsulation. The 2D mechanical admittance plot clearly shows this to be the case with load transfer throughout the length of the bolt. This bolt will thus be classified as a serviceable bolt with good anchorage (see Figure 19).

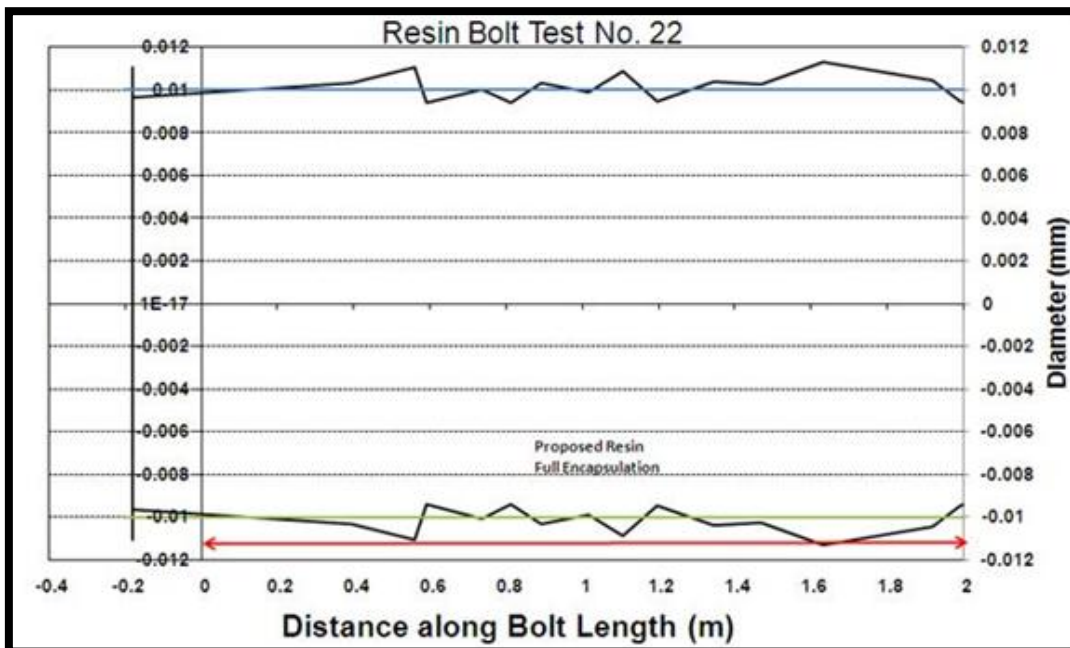


Fig 19 - 2D Plot for Resin Bolt Test No.22.

## Friction Bolts

A summary of the test results are provided below in Table 11.

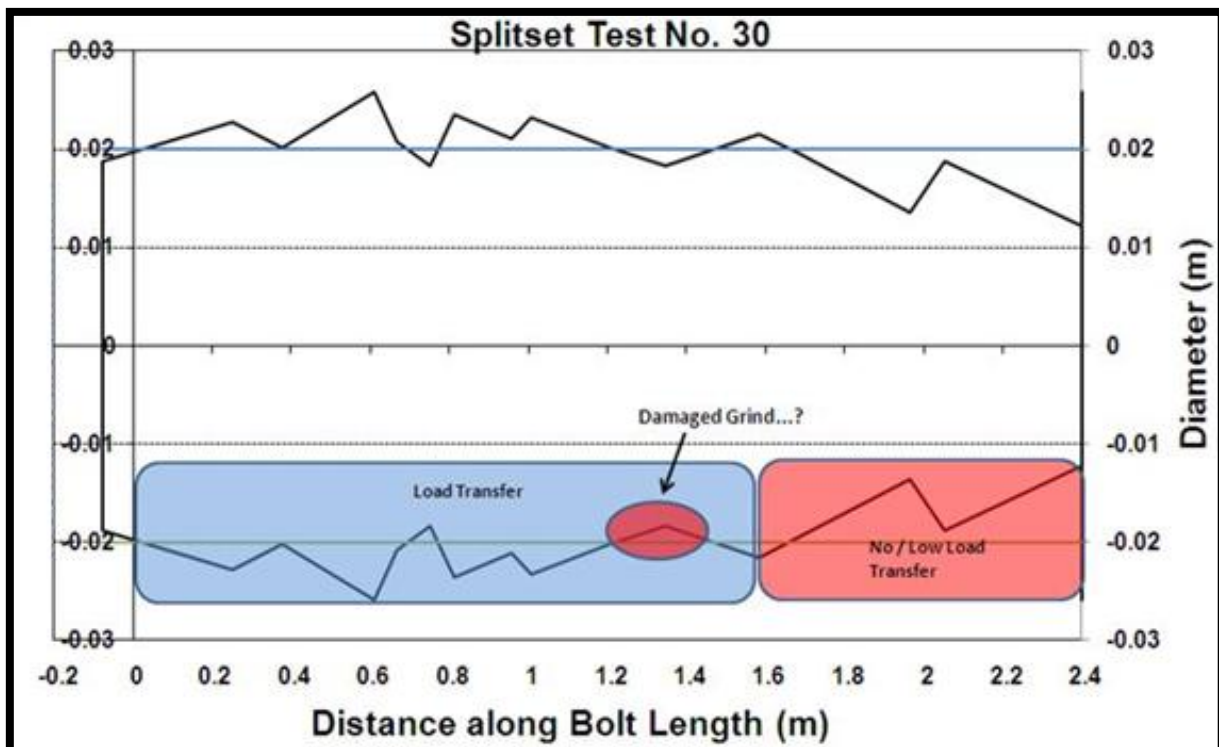
**Table 11 – Friction Bolts test result summary.**

Test	Element Test Number	Bolt Type	Location	Nominal Length of Element (m)	Bar Stiffness (t/mm)	"E" max (t/mm)	"E" min (t/mm)
<a href="#">MSS30</a>	30	Friction Bolt	6 Level 5053	2.4	6.2	15.6	6.7
<a href="#">MSS31</a>	31	Friction Bolt	6 Level 5053	2.4	19.1	13.2	6.8
<a href="#">MSS32</a>	32	Friction Bolt	6 Level 5053	2.4	16.1	13.2	7.5
<a href="#">MSS34</a>	34	Friction Bolt	6 Level 5053	2.4	17.1	13.8	8.5
<a href="#">MSS35</a>	35	Friction Bolt	6 Level 5053	2.4	8.0	18.2	9.0

The test results for the Friction bolts are still under scrutiny as an appropriate diameter is still under investigation for the friction bolts. Hence the absolute values provided above may not be the accurate representation for the friction bolts as the stiffness principal value is shown with much higher values than the actual friction bolt tensile strength. With more tests done on friction bolts a more accurate stiffness value will be determined. The mechanical admittance plot however has provided the much required confidence with regard to signal continuity or admittance.

The following comments are made regarding the calibration tests for the friction stabiliser tests data interpretation:

- Test 30 was a 2.4m long friction stabiliser with an area that was damaged (grind) at round 1.2m. The 2D mechanical admittance plot clearly shows mechanical admittance from the collar to about 1.2m and then no load transfer detected from about 1.7m to the toe of the friction stabiliser (see Figure 20).



**Fig 20 - 2D Plot for Splitset Test No.30.**

- Test 31 appear to have very similar mechanical admittance as test 30 with the the 2D mechanical admittance plot clearly showing mechanical admittance from the collar to about 1.7m and then no load transfer detected from about 1.7m to the toe of the friction stabiliser.
- Test 35 appear to have a different mechanical admittance as the two previous tests (i.e. 30 and 31) with the 2D mechanical admittance plot showing an area of no load transfer between 0.6m to 1.1m and no load transfer towards the toe of the bolt. The no load transfer towards the toe agrees well with the friction bolt's tapered end.
- Test 34 was quite an interesting test. The friction bolt was damaged (i.e. cut slots) by George Fisher personnel at 1.2m from the collar. During the installation the friction bolt collapsed and was driven into itself. The test results or mechanical admittance plot shows that no load transfer occurred after 1.2m which agrees well with the actual bolt collapse (see Figure 21).

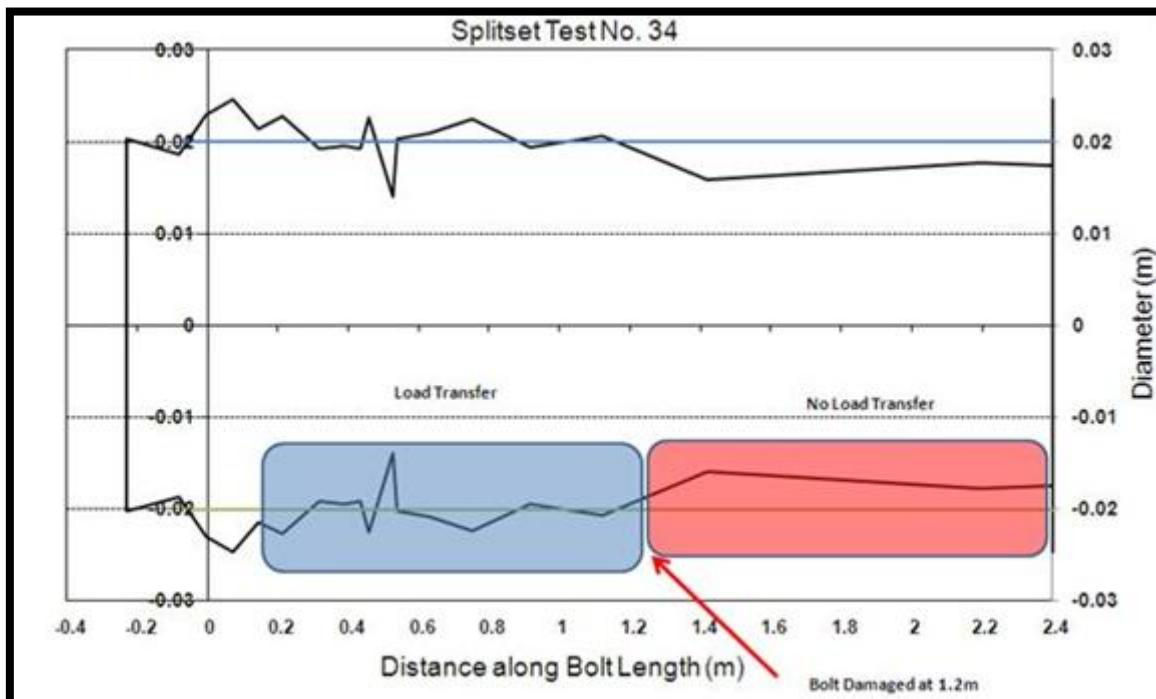


Fig 21 - 2D Plot for Splitset Test No.34.

## CONCLUSIONS

The non-destructive calibration testing conducted using the Modshock System will provide George Fisher rock mechanics personnel with some confidence in detecting rock reinforcement subject to corrosion and/or poor quality installation. The rock reinforcement installation for calibration purposes was done in a semi controlled environment where bolts were installed to simulate either poor installation techniques or damaged / corroded elements.

The test work on the cable bolts was slightly affected by gaps behind the plates (i.e. plates not tight with excavation surface – this is caused by the uneven nature of the rock surface). This had a distorting affect on the signals, some of which could not be relied on for analysis purposes and thus required several attempts to obtain a proper / valid signal.

During our investigation (calibration testing) on the cable bolts we noticed an interesting disturbance phenomenon in the 2D mechanical admittance plot for all the cable bolts tests and which were previously noticed when testing cable bolts at another mine. This relates to the first part of the mechanical admittance

plot. Following an investigation into cable bolt behaviour an article was found describing load / strain dissipating from the collar, which could be an explanation for the disturbance in the 2D mechanical admittance plot. This phenomenon however would need to be confirmed with some instrumented bolts.

The test results for the calibration bolts showed that the grout / resin embedded and free length of the cable bolts and resin bolts were clearly detected using the Modshock System. However the anticipated grout / resin locations for a few of the test specimens could not be accurately picked, as the location of the grout / resin appeared to be in a slightly different location than what has been proposed. Discussions surrounding this let us to believe that the lack of proper control (i.e. not laboratory environment) during the grout / resin installation could very well be the reason for detecting some of the resin / grout installations in another location.

As the main use for the Modshock system is mainly to determine the integrity of rock reinforcement elements, the calibration testing provided us with enough confidence to use the Modshock system as a quality control tool. The two loading calibration tests (i.e. cumulative load pull tests compared with load stiffness calculations from the Modshock Tests for the elastic deformation range) conducted on resin bolts are inconclusive at this stage as only one of the two tests had positive results. Tests 8-15 (i.e. resin bolt encapsulation of 0.5m) showed a gradual increase in calculated bar stiffness (i.e. 0.6 - 3.9 tonnes/mm) from test 8 through to test 15, which indicates that the Modshock system do capture the bolt load response. There was also noticeable correlation between the load pull tests and Modshock calculated load values for these tests. Hence it is acknowledge as indicated in our paper published at the international tunnelling conference in Vancouver (Hartman, et al., 2010b) that the following work is required to increase confidence in other data interpretation:

- Calibration testing to confirm the elastic load increase in tendons and solid rebars as referred to in this paper and
- Confirmation of two dimensional graph amplitude variance and descriptive analysis.

The test results for the friction bolts are still under scrutiny as an appropriate diameter is still under investigation for the friction bolts. Hence the absolute values provided in this report may not be an accurate representation for the friction bolts as the stiffness principal values obtained are much higher than the actual friction bolt tensile strength. But with more tests done on friction bolts a more accurate stiffness value will be determined. The mechanical admittance plot however has provided the much required confidence with regard to signal continuity or admittance as these results are in agreement with friction bolt behaviour (i.e. low or no load transfer towards the toe of the hole).

The non destructive testing can be employed to improve understanding of rock reinforcement elements loading conditions and verify the following important aspects of ground support (Hartman et al, 2010b):

- Verification of current design – this relates to cable bolt anchorage e.g. if the design or selection is for 10m cable bolts and the tests indicates poor anchorage (i.e. a section of around 2m – critical embedment length) or poor load transfer in the 2D mechanical admittance plot as a result of poor grouting and inefficient bonding, it would indicate that the design have been compromised.
- Integrity check of rock reinforcement in main access ways e.g. decline where the bolts need to be intact throughout the life of the excavation – this would then be a check for corrosion (significant volume loss) and/or overstressing where the calculated bolt stiffness is high.
- The third but very important check is for the general quality of ground support installation and this would then become part of the mine's or underground construction's ground support system frequent quality integrity check.

## ACKNOWLEDGEMENTS

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## FIGURE CAPTIONS

**Fig 1 – Hydraulic Pull testing device used at the George Fisher Mine.**

**Fig 2 – George Fisher Lead-Zinc Mine (2009 – XSTRATA Operations).**

**Fig 3 – Cable Bolt Diagram.**

**Fig 4 – Thread Bar Posimix.**

**Fig 5 – Friction Bolt 47mm diameter diagram.**

**Fig 6 – Schematic illustrating single strand cable bolt calibration set-up.**

**Fig 7 – Schematic illustrating twin strand cable bolt calibration set-up.**

**Fig 8 – Schematic illustrating resin bolts calibration set-up.**

**Fig 9 – Schematic illustrating resin bolts calibration set-up.**

**Fig 10 – Corroded bolt, 16 level crib room.**

**Fig 11 - 2D Mechanical Admittance Plot for Single Strand Cable Test No.4.**

**Fig 12 – Collar load plotted against A, microstrain (load profile curve) and B, distance from head of cable (load correlation curve, Martin et al (2004)).**

**Fig 13 - 2D Plot for Single Strand Cable Test No.3.**

**Fig 14 - 2D Plot for Single Strand Cable Test No.34.**

**Fig 15 - 2D Plot for Twin Strand Cable Test No.2.**

**Fig 16 - 2D Plot for Twin Strand Cable Test No.41.**

**Fig 17 - 2D Plot for Resin Bolt Test No.27.**

**Fig 18 – Load vs Deformation graph for bolt test 8 -15 (Modshock vs Pull Test Results).**

**Fig 19 - 2D Plot for Resin Bolt Test No.22.**

**Fig 20 - 2D Plot for Splitset Test No.30.**

**Fig 21 - 2D Plot for Splitset Test No.34.**

## **TABLE CAPTIONS**

**Table 1 – Mechanical Properties for 15.2mm diameter Cable Bolt.**

**Table 2 – Mechanical Properties for Thread bar Posimix.**

**Table 3 – Mechanical Properties for the Friction Bolt.**

**Table 4 – Single Strand Cable Bolts Calibration Set-up.**

**Table 5 – Twin Strand Cable Bolts Calibration Set-up.**

**Table 6 – Resin Bolt Calibration Set-up.**

**Table 7 – Friction Bolts Calibration Set-up.**

**Table 8 – Single Strand Cable Bolts test result summary.**

**Table 9 – Twin Strand Cable Bolts test result summary.**

**Table 10 – Resin Bolts test result summary.**

**Table 11 – Friction Bolts test result summary.**