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Non destructive integrity testing of rock reinforcement elements in Australian mines

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NON DESTRUCTIVE INTEGRITY TESTING OF ROCK REINFORCEMENT ELEMENTS IN AUSTRALIAN MINES

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ABSTRACT: Non-destructive testing, used to study the integrity of the bolting systems in underground mining and civil construction industries, as an alternative method to the current hydraulic pull testing practice, is described. Non-destructive tests were carried out on a total of 227 bolts, comprising 89 rebar type bolts, 124 cable bolts and 14 splitsets were tested in four mines across Australia. The purpose of these tests was to confirm the validity of the testing methodology for rock reinforcement systems used in mines and provide reassurance on bolt's integrity, which could have been compromised during installation or affected by in-situ aggressive conditions causing corrosion. A complex stress wave analysis package, based on the processing of clear seismic signals imparted into the rock reinforcement element, was used. The seismic signals are processed by "Fourier Transform" into various criteria, which can be used to produce models of the elements, such as mechanical admittance, frequency spectra and velocity. These components are then used in the final modelling of the rock reinforcement element under analysis. The non-destructive integrity testing of rock reinforcement at these mines indicated that there is opportunity to further investigate the potential in effectively managing the risk of ground failure incidents in underground openings.

INTRODUCTION

The traditional pull out tests currently used for rock reinforcement testing is not considered an effective tool for the detection of compromised rockbolt systems used for ground control in underground mining and civil construction industries. It is acknowledged that pull tests have an important role to play in static and quasi static ground support designs in determining critical bond lengths through short anchorage testing. However anchorage capacity testing does not provide an underground operation with any reassurance regarding bolt integrity, which could have been compromised during installation or affected by in-situ aggressive conditions that cause corrosion.

Non-Destructive rock reinforcement integrity testing conducted at four Australian Mines (i.e. Western Australia, Queensland, New South Wales and Victoria) have shown that there is potential to optimise this testing method. A total of 199 bolts comprising 61 rebar type bolts, 124 cable bolts and 14 split sets have been tested to date. The non-destructive rock reinforcement integrity testing was 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. The non-destructive integrity testing of rock reinforcement at these mines indicated that there is opportunity to further investigate the potential in effectively managing the risk of fall of ground incidents at underground mine and construction sites.

BACKGROUND INFORMATION

In simple terms the modified shock test, which is 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

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Moses in 1973, but British engineers had not exploited this technique to the extent that could have been useful to them because of a lack of knowledge 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 the interpretation. The experience of testing many thousands of piles led to the technique being applied with more confidence to testing piles on sites as a norm. 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 (Davis and Dunn, 1974). The vibration method used for pile testing has been slightly modified for rock reinforcement testing. Thus instead of using a vibrator (i.e. pulse generator to excite the pile), velocity transducer and accelerometer the Modshock system only incorporates a tapping device in order to excite the bolt, low frequency geophones (i.e. horizontal, vertical and upside down transducers) and an analogue / digital converter which converts the signal from the transducer into a digital format.

The analysis for rock reinforcement is similar and 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 check rock reinforcement integrity and to analyse the surrounding influences (i.e. ground deformation). 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 (Higgs and Tongue, 1999). 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 yrs (Higgs, 1975). Integrity Testing Pty Ltd (i.e. developers of the Modshock system) has for over 15 yrs carried out testing of long length steel rods, either as strand or solid steel bars. The most notable project was for BHP, who 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 is generally with the lengths in excess of 5 m.

TESTING SET-UP AND METHOD

There are four components to the system (Figure 1-4):

1. ***A Toughbook / Notebook*** - this is used to collect data and providing power via a USB cable for the (see Figure 1).

Figure 1 - Notebook in operation (by Wouter Hartman) at the Fosterville Underground Gold Mine

2. ***Analogue/Digital Converter encased in closed unit*** - this converts the signal from the transducer into a digital format. The converter is soft wired to the transducer (see Figure 2).

Figure 2 - Analogue/Digital Converter encased in closed unit for coal mine operations

3. ***Transducer –*** *which is* held at the end of bolt (i.e. collar of hole – see Figure 3) during the test. A signal / pulse is obtained, which is generated by a small hammer.

Figure 3 - Photo showing transducer (vertical) held at the end of bolt (i.e. collar of hole) at Manadalong Coal Mine

4. ***A small hammer or tapping device*** (see Figure 4) - This has to make contact against the plate or nut of the bolt during the test.

Figure 4 - Photo showing tapping device that is used to make contact with the nut of resin bolt

TEST OUTPUT

A valid seismic signal (see Figure 5) is obtained through the Modshock system and is one of the main criteria by which a test is accepted or rejected. The graph displays velocity on the vertical axis and time on the horizontal axis. The blue line represents the seismic signal; where as the pink line represents the commencement of element analysis.

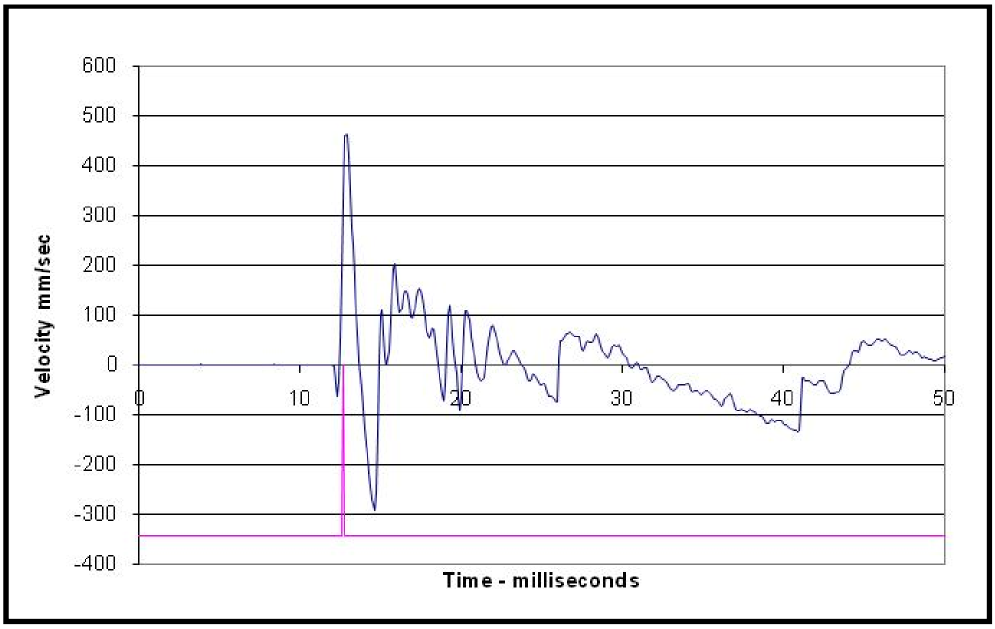

Table 5 - Diagram showing valid seismic signal obtained by transducer (geophone)

The operator in the field can at the time of testing identify which element (bolt) are serviceable and then concentrate on the rock reinforcement elements that have shown anomalies. For the elements with anomalies a two-dimensional graph of the test can be obtained and presented after the analysis has been carried out (see Figure 6).

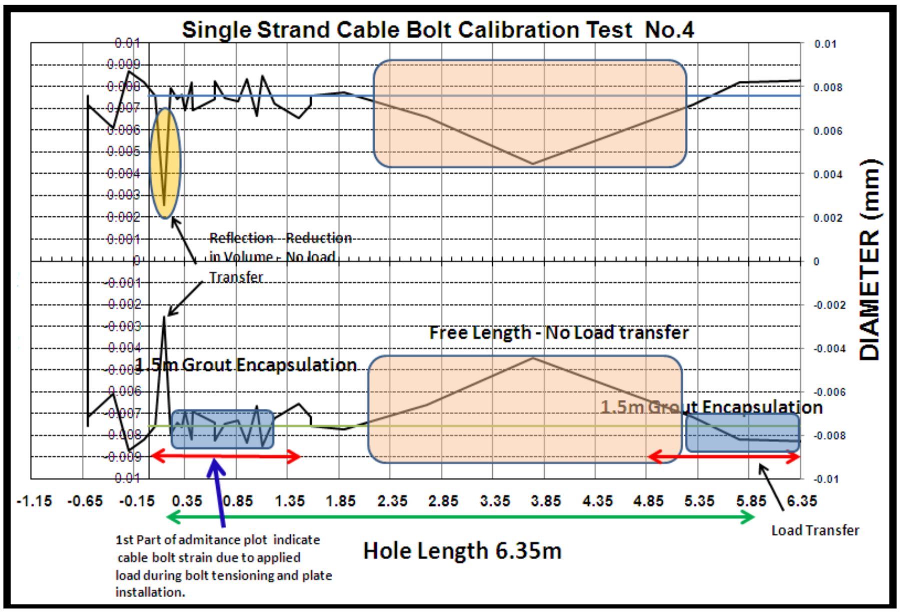

Table 6 - Two dimensional graph showing structural stiffness of rock reinforcement element with diameter used as a guide

The two opposing curved black lines on the graph represent structural stiffness through good embedment or load transfer. The top (blue) and bottom (green) horizontal lines in the graph collectively represent the element's full diameter. The structural stiffness presented in the two dimensional plot together with the element's diameter are used to indicate whether any disturbance (i.e. bolt necking, bolt volume reduction through corrosion, bolt shearing (Hartman, 2003) and/or ineffective grout or resin embedment) or reflection point can be detected during testing. The graph is an example of disturbance (reflection) where grouting was deliberately placed towards the toe end of the bolt as part of a calibration program at the Sunrise Dam Mine (WA). The graph clearly shows good load transfer or embedment towards the toe end of the bolt.

One of the vital pieces of information obtained from the non-destructive test is the "Head Stiffness" as this is the basis of all the load predictions and it also indicates the serviceability of the total bolt system. The head stiffness is the "E" prime of the bolt, measured as a direct measurement of the first part of the "structural stiffness plot", and is similar to a load/displacement graph for a pull out test.

The "bolt head stiffness (tonnes/mm)" is compared to the two model stiffness values "E" min and "E" max. "E" min is a bolt model with the bolt pinned at its toe (end anchored) but with no clamping (no resin or grouting) along its length. "E" max is a bolt model with an infinite rigid base and "*clamped*" (full column grouted / resin) along its length. These models are based on the work carried out by Davis & Dunn (1974).

The "Stiffness" value of the bolt is a good indicator of the serviceability of the bolt, but cannot be used in its entirety to give a serviceability rating for the bolt, as a number of factors come into affect when measuring the stiffness. The measurement of the stiffness can be affected by the fixity of the end of the bolt, the bonding effect of the resin/grout around the bolt and the bond from the rock to the resin/grout to ensure a fully encapsulated scenario of the bolt.

RECENT FINDINGS

Detection of rock reinforcement element length

In a recent test at the Fosterville Gold Mine cable bolt lengths were accurately depicted following confirmation from the mine. The test set-up incorporated 10 m and 8 m lengths as input parameters for the cable bolt testing. Most of the bolts were confirmed to be either 8 m or 6 m in length (see below Figure 7 for final interpretation of two dimensional structural stiffness plot).

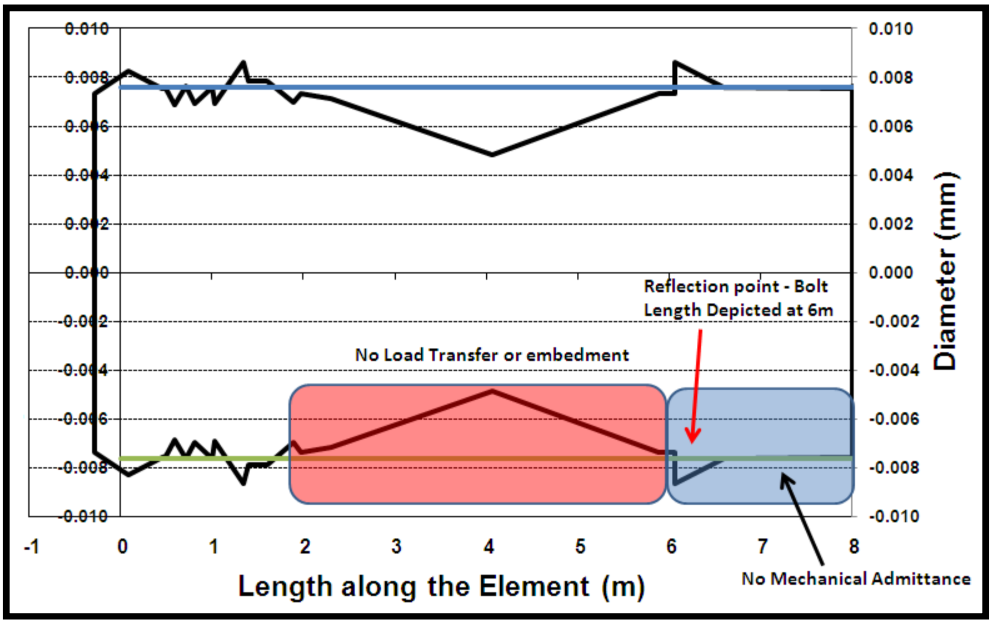

Table 7 - Two dimensional graph showing confirmation of twin stand cable bolt 6m length following initial 8m input parameter

The above graph clearly shows bolt length to be around 6 m following test input parameter set to 8 m. The bolt length was later confirmed by the mine to be a 6 m twin strand cable bolt.

Detection of poor grout / resin installation and shorter anchor

Both Figure 6 and 7 above are prime examples of poor grouting. Figure 6 is an example of a calibration bolt with known grouting embedment at the toe and collar. Figure 7 is a two-dimensional graph of a *"full column grouted"* twin strand cable bolt tested at the Fosterville Gold Mine showing clear signs of a defect (i.e. grout deficiency) between 3 m and 4 m. In addition, this graph also shows that the cable bolt length to be 6 m instead of 8 m.

Confirmation of good quality resin installation on solid rebars and Hi-Tens end anchored cable bolts

Test completed at Mandalong Coal Mine shows that the resin installation practices at Mandalong appear to be of good quality when interpreting the two dimensional graphs (see Figure 8 below) and calculated load. Figure 8 indicates good embedment (structural stiffness) along the length of the resin bolt.

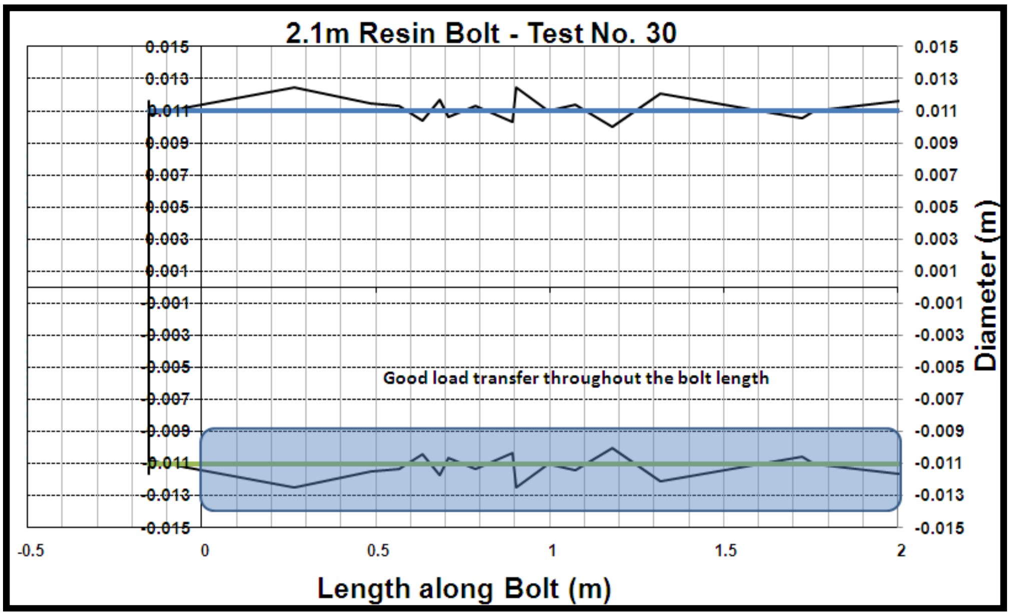

Table 8 - Two dimensional graph showing good embedment achieved along the length of the 2.1 m resin anchor installation

The Hi-Tens cable bolts are installed using a 1 200 mm long slow set resin which is inserted into the hole using a conduit to push it right to the back of the hole. The Hi-Tens tendon is inserted into the hole until it reaches the base of the resin. The bolt is spun through the resin for about 30 seconds to activate the quick set resin. The plate, barrel and wedge are installed with a tensioner to 20 tonnes. Tests conducted on the Hi-Tens tendon showed an interesting two dimensional graph where the resin installation is limited to the toe area of the bolt / hole as per design. A free anchor length of around 4.2m is maintained with the 2D plot showing either signs of stress increase or noise close to the collar. We have reason to believe that it could be related to an increase in stiffness / strain in the bolt as this was previously noticed when testing cable bolts at the Sunrise Dam Gold Mine and other mines. This phenomena relates to the first part of the two dimensional graph (see below Figure 9 – Hi Tension tendon – Test No. 9 – Mandalong Coal).

In 2004 Martin *et al*. showed that a critical load is required before the cable bolt, at a given location, would 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 10 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 would sense load only when the collar load exceeds 25.4 × 2 043 N/cm.

Figure 10 shows some similarity to the load vs dissipation rate graph of a collaborative investigation, conducted in 2004, into the behaviour of cable bolts. The collaborative work was carried out at the University of Saskatchewan, Saskatoon; Itasca Consulting Group, Inc., Minneapolis; University of British Columbia, Vancouver (BC) and the National Institute for Occupational Safety and Health (NIOSH). The study provided valuable information regarding their loading and strain behaviour. The above phenomenon, however, would need to be confirmed with strain gauged cable bolts. The cable bolts could then potentially be subjected to various loads and simultaneously tested using the Modshock system to compare actual loads with analysed elastic loads for correlation.

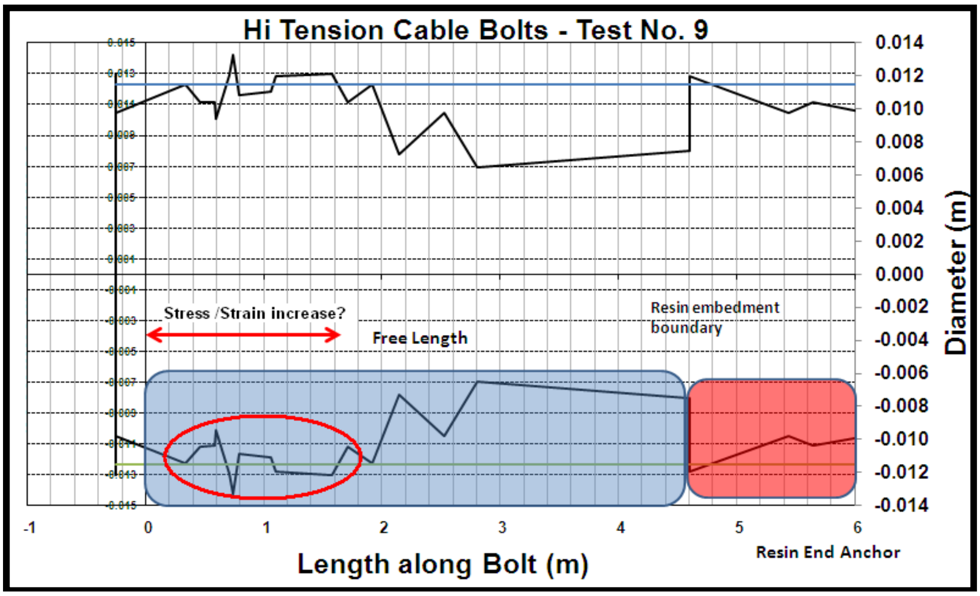

Table 9 - Two dimensional graph showing confirmation of end anchor resin embedment and possible stress / strain increase in close proximity of hole collar

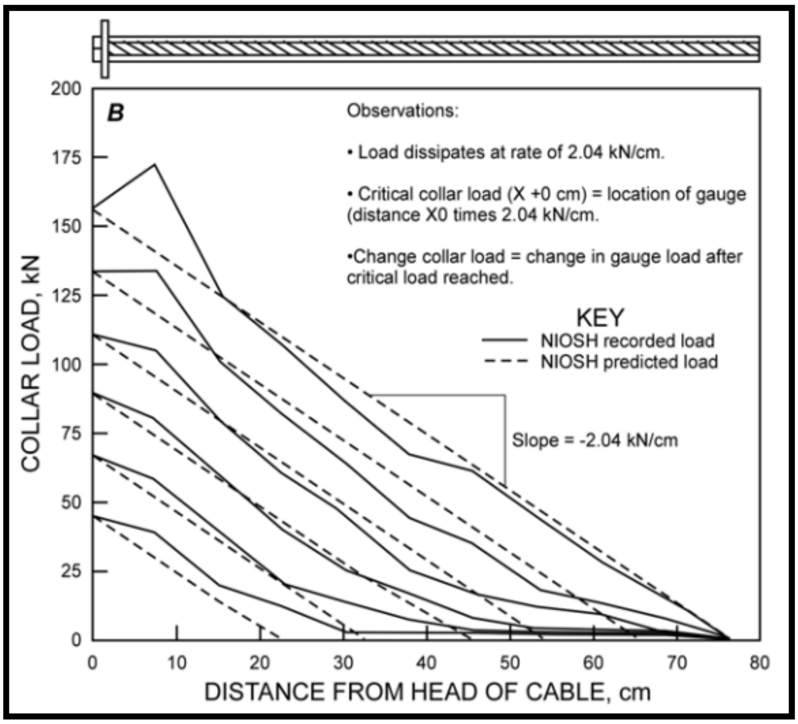

Table 10 - Collar load plotted against A, microstrain (load profile curve) and B, distance from head of cable (load correlation curve, Martin et al.(2004))

TESTS RESULTS

Non-destructive tests were carried out on a total of 227 bolts, comprising 89 rebar type bolts, 124 cable bolts and 14 splitsets were tested in four mines across Australia (See Table 1 below outlining different types of bolts tested).

Table 1 - Different type of bolts tested

Stiff Splitsets	Splitsets or Friction Bolts	Resin Solid Rebar	Single Strand Cable Bolt	Multi Strand Cable Bolt	Hi Tensile Cable Bolt
		14		31	
1	9	4	44	15	
	4	34	7	8	
		37			19

Of the 227 bolts tested 36 were calibration bolts comprising of resin bolts, twin and single strand cable bolts and split sets. 191 Bolts were tested for defects related to insufficient grout / resin which affect the anchorage or anywhere along the length of the bolt; bolts affected by corrosion displaying significant volume loss and reduced load transfer and/or bolts displaying low calculated stiffness indicating low load transfer or poor encapsulation. These defects or significant issues were presented through a simplified bolt serviceability classification system (see below Table 2).

Table 2 - Simplified bolt serviceability classification system

Category 1.	A perfect bolt in perfect rock conditions – in our opinion this will rarely occur
Category 2.	A bolt which we consider is serviceable in that it has good anchorage, good embedment / load transfer along the length of the bolt and reasonable rock/grout/resin contact. Conform to design criteria e.g. end anchored resin bolts.
Category 3.	A bolt that has some deficiencies in reduced anchor strength, poor grout/resin/rock contact or loss of bolt section. The remarks section will identify the possible source of the deficiency.
Category 4.	A bolt that has either failed; is loose or at a point where additional load on the bolt could lead to failure; or a loss of bolt section which is critical e.g. anchorage area where the 400mm critical bond length has been affected

Table 3 - below outlines the bolt classification results for the 191 bolts tested

Poor Signal	Inconclusive	1	2	3	4	Bolt Types
			14	14	9	Twin Strand Cable Bolts
2	4		7	27	2	Single Strand Cable Bolts
			11	8		Hi-Tens Cable Bolts
			8	41	34	Resin Bolts
1				3	6	Split sets
3	4	0	40	93	51	191
2	2	0	21	49	27	Percentages

70% of the 191 bolts tested were classified as serviceable but with 49% of the bolts tested, some kind of defect (i.e. suspect anchorage, low load transfer and/or volume reduction) have been detected. Almost 30% of the 191 bolts tested were classified as non-serviceable with the majority of the bolts showing a deficiency in end anchorage as per mine design and / or overstressed bolts due to excessive ground deformation. 2% Of the 191 bolts tested have been classified as inconclusive. This relates to bolts being identified as short bolts or very poor anchorage but completely out of character for the type of bolt.

CONCLUSIONS

Ground support quality control has been a high priority for most mines but remained a high risk due to the uncertainty in the current bolt integrity testing procedure of pull testing. The use of non-destructive technology to test for defects or poor quality installation techniques are showing an enormous opportunity in effectively manage this geotechnical risk. It has been found that verification of rock reinforcement designs (i.e. bolt lengths and full column resin/grout installations) and integrity confirmation are two of the biggest challenges for geotechnical engineers and mine management. We are confident that this non-destructive integrity testing technique is a step towards reducing the uncertainty in quality control of rock reinforcement installations.

It is acknowledged that in order to increase confidence in other data interpretation the following are required:

- 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.

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