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Simulating static pull tests, shear tests and dynamic drop tests to identify basic parameters for subsequent support design

PM Dight *Australian Centre for Geomechanics, The University of Western Australia, Australia*

Abstract

There has been a proliferation of dynamic bolts and their testing for support based on laboratory testing and field testing. The advantage of the laboratory testing is that the boundary conditions such as the precision of the hole, the stiffness of the 'rock' and the quality of the grout/resin installation can be controlled. The field tests are valuable so long as the boundary conditions affecting the bolt response are well understood. However, the industry is silent on how to take the test results and apply them in the ground pertaining to an operation. This paper will show that not only can the laboratory results be readily simulated using well-established geomechanical relationships applied to the known boundary conditions, but with an understanding of the inputs, the field conditions can be replicated showing the likely support response. Design can then follow for operations with more certainty.

Keywords: *simulation, static support, dynamic support, shear behaviour, laboratory testing, field testing, bolt behaviour, geomechanical properties, design*

1 Introduction

Bolt testing and, more particularly, pull testing on short encapsulated bolts has been undertaken since the mid 1970s (Fuller & Cox 1975), both in the laboratory and in the field. There have been many test facilities constructed in Australia, Canada, France, Norway, Sweden and South Africa, and field tests undertaken in Canada, Australia, the USA, Colombia, Sweden and South Africa (e.g. Dight 1982; Hyett et al. 1992; Stillborg 1994; Benmokrane et al. 1995; Tannant et al. 1995; Ito et al. 2001; Stacey & Ortlepp 2001; Aziz et al. 2003; Player et al. 2004; Compton & Oyler 2005; Jaramillo 1996; Varden 2005; Van Sint Jan & Palape 2007; Hadjigeorgiou & Potvin 2007; Villaescusa et al. 2008; Player et al. 2009; Li 2010; Blanco Martín et al. 2011; Bucher et al. 2013; Darlington et al. 2018; Whiting 2017; Hadjigeorgiou & Tomasone 2018; Cai & Kaiser 2018; Thenevin et al. 2019; Brändle & Fonseca 2019; Hagen et al. 2020; Zhao et al. 2021). The investigators at the facilities have looked at the load transfer capacities of bolts, mesh and plates under static and dynamic conditions.

The purpose of using short encapsulation lengths is to determine the bond strength characteristics of the bolt. Such properties are important in the modelling of bolt behaviour subject to fractures opening in the rock that activate the support to resist (Fuller & O'Grady 1994) deformation. Due to a wide range of techniques, Chen et al. (2015) revised the short length encapsulation pull test (SLEP) to better define the approach.

The dynamic tests have been focused on providing comparisons of energy absorption where the energy will work to arrest the damage in the rock mass resulting from a strainburst. The tests can be single or direct (i.e. the load is applied to the bolt head) or double (also called indirect) where there is a split in the confining tube, simulating loading within the rock mass.

Mine sites now specify the required energy absorption and displacement limits; if based just on laboratory results, they could be misleading, which is where in situ tests become critical (Darlington et al. 2018).

In a laboratory drop test, the boundary conditions can be defined. In most cases, a steel tube of known internal diameter and thickness is used surrounding the bolt – typically, this equates to a rock mass modulus of between 50 and 66 GPa, which is a reasonable facsimile for many brittle rocks. It is more difficult with field tests because of the ground conditions; hence back-analysis is required.

Cai & Kaiser (2022) advise that due to a lack of a testing standards, it is difficult to compare published rockbolt performance data and it is often a challenging task to select the most appropriate rockbolts. The approach in this paper addresses this concern.

2 Rockbolt simulations: static tests and dynamic tests in the axial direction in the laboratory

Much of the focus in the recent testing work has been on the properties of the bolt. However, it is important not to lose sight of the objective that the purpose of the reinforcing (bolt, nut, plate, mesh etc.) is to support the rock. The same bolt characteristics will apply in a low-stiffness, weak ground as in a stiff, massive rock. What differs, is the rock mass stiffness and, possibly, the grout quality and strength.

The bolts are installed in a steel tube of known diameter and thickness using cement or resin grout. Quality control on the cement grouts is easily achieved with testing after seven or 28 days. The test size is usually 50 mm in diameter and 100 mm long. The literature is silent on the testing of resin used in the laboratory tests relying on the manufacturer's advice. When tested, resins are more often prepared in a 40 mm cube or 40 × 80 mm prism. Hence, care needs to be exercised when using empirical relationships to compare cementitious grout strengths to resin strengths.

A steel tube with a known diameter and thickness provides a constant stiffness to the test (Hyett et al. 1992). When cement blocks are used as the confinement and the strength is quoted (e.g. uniaxial compressive strength (UCS) = 60 MPa), but the modulus is not quoted, it has been assumed that the modulus is 330 times the strength (i.e. E = 20 GPa).

The radial stiffness (K) of the pipes used for confinement can be calculated from thick wall cylinder theory, (Hyett et al. 1992) according to Equation 1:

$$K = (2E_s/(1-v_s))({d_o}^2 - {d_i}^2)/(d_i\left((1-2v_s)d_i^2 + d_o^2\right)) \tag{1}$$

where:

d_o = outside diameter.

d_i = internal diameter.

v_s = Poisson's ratio of steel.

E_s = modulus of steel.

This can then be related to the rock mass modulus by Equation 2:

$$E_r = \frac{K(1+v_r)d_i}{2000} \tag{2}$$

where:

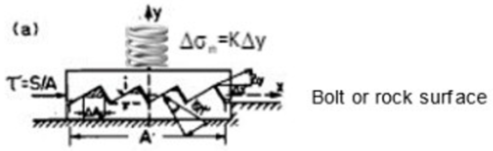
v_r = Poisson's ratio of rock mass.

Using a steel tube that has an outside diameter of 60.3 mm, an internal diameter of 49.5 mm, a steel modulus of 210 GPa and a steel Poisson's ratio of 0.28, this would yield a stiffness (K) of 1,667 MPa/mm. If the rock Poisson's ratio was 0.226, then the equivalent rock mass modulus would be 50.6 GPa.

An algorithm that was originally developed to analyse side socketed piles (Dight & Chiu 1981) has been successfully adapted to handle bolt pull out tests and performance of fibre-reinforced shotcrete (Manca et al. 2017). It has also been shown to work with bolt push tests (Varden 2005).

This is based on the aforementioned concept of a constant stiffness and the energy-based shear equation developed by Ladanyi & Archambault (1969). The key assumption is that for large-scale deformation, the bolt is rigid within the grout and the steel tube encapsulating the bolt/grout is a large spring. A copy of the steps required is presented in Figure 1. The bolt and geotechnical input parameters comprise the bolt strength and deformation properties, the bolt embedment length and de-bonded length, the surface profile (i.e. what causes the rock and/or grout to dilate), the bolt diameter, the friction angle between the bolt and grout (assuming this is the interface that shears), the grout compressive strength, and tensile strength. The stiffness is a function of the internal and external diameter of the encapsulating steel tube, Poisson's ratio and steel modulus. Analysis of the pull test results can then proceed based on very small incremental steps.

k1, k2 empirical constants
K, $\varnothing_r$, σ_0, q_u, T_o obtained from sample
L_1, $\tan i_o$ obtained from profile
$\sigma_n = \sigma_0$, $m=(n+1)^{1/2}$, $n=q_u/T_0$
Step 1
$x=0$, $\Delta x=0.001$
Step 2
$x=x+\Delta x$
$\dot{v}=(1-\sigma_n/(\eta q_u))^{k2}\tan i_o$
$\Delta y=\Delta x^* \dot{v}$
$y=y+\Delta y$
$\Delta\sigma_n=K\Delta y$
$\sigma_n=\sigma_n+\Delta\sigma_n$
$\eta=1-x/L_1$
$a_s=(\sigma_n/(\eta q_u))^{k1}$
$S_1=a_s\eta q_u((m-1)/n)(1+n\sigma_n/(\eta q_u))^{1/2}$
$S_2=\sigma_n(1-a_s)(\dot{v}+\tan\varnothing_r)$
$S_3=1-(1-a_s)(\dot{v}\tan\varnothing_r)$
$\tau=(S_1+S_2)/S_3$
Write x, y, τ, σ_n, $\dot{v}$



Based on Ladanyi and Archambault, 1969
$k_1=1.5$, $k_2=4$
K= stiffness of rockmass
Φ_r = base friction angle
σ_o = initial confining stress
q_u = compressive strength of weakest material
To = tensile strength
L_1 = length of asperity
i_o = initial dilation angle
a_s =area of the asperities
$\dot{v}$ = dilation

Figure 1 A simple algorithm to analyse static and dynamic behaviour of pull tests

Observation of published tests show that the dynamic behaviour is controlled by the de-bonded length and that the shape of the curve is similar if the bolt is de-bonded or not, except for the extra extension with the de-bonded bolt.

The literature tends to be silent on the influence of the boundary conditions and, in some cases, authors assume the laboratory result can be used in design as the maximum allowable, deteriorating according to displacement or movement of the rock mass following excavation. In laboratory simulations using large concrete blocks as the encapsulating material, i.e. SINTEF (Stiftelsen for industriell og teknisk forskning or The Foundation for Industrial and Technical Research), the modulus of the concrete is not stated. This leaves users of the data in the published literature essentially without knowledge of the boundary conditions.

The test results used to illustrate the approach are presented on the DSI Underground website (DSI Underground 2023), as shown in Figure 2, for a 2.4 m long bolt

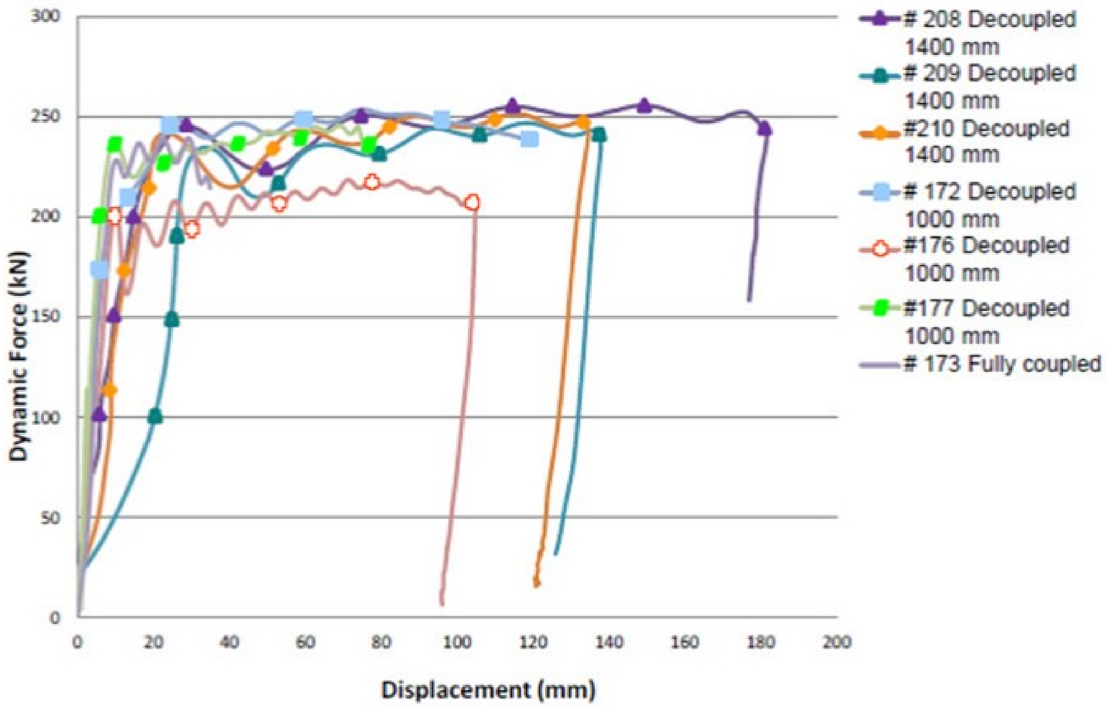


Figure 2 Results of static and dynamic testing conducted at Western Australian School of Mines (WASM) test facility. The static test is shown as #173 fully coupled

The bolt under investigation/analysis was a 20 mm diameter 2.4 m long Posi-bolt that was comprised of a wire helix wrapped around a deformed bolt (Figure 3). The helix improves the grout/resin mixing, minimising ‘gloving’, and assists in centring the bolt in a 38 mm diameter hole. The de-bonded section separates the bolt from the grout. A 600 mm section of the bolt is grouted adjacent to the collar.

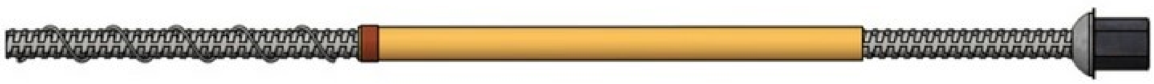


Figure 3 20 mm diameter Posi-bolt 2.4 m long

Examination of the test results in Figure 2 shows a static test. An analysis of this result using the algorithm is shown in Figure 4.

The critical parameters for this simulation comprise the rock mass modulus (66 GPa), the base friction angle between the grout and the bolt (20°), the dilation, which relates to the local deformities or the non-axiality of the bolt (0.05°), and the grout strength (24 MPa). The length of embedment was 1 m. As can be seen in Figure 4, the fit is very good.

The next simulation is for the dynamic tests on 1 m of de-coupling or de-bonding. The result of the simulation is shown in Figure 5.

The key parameter that changes between the static test and these dynamic tests is the compressive strength of the grout which has been reduced to 18 MPa to ensure a reasonable fit. All other parameters remain the same as for the static test.

Figure 6 shows the results when the de-bonded length is increased to 1.4 m. There is no change between the test for a de-bonded length of 1 m and the simulation for the 1.4 m length.

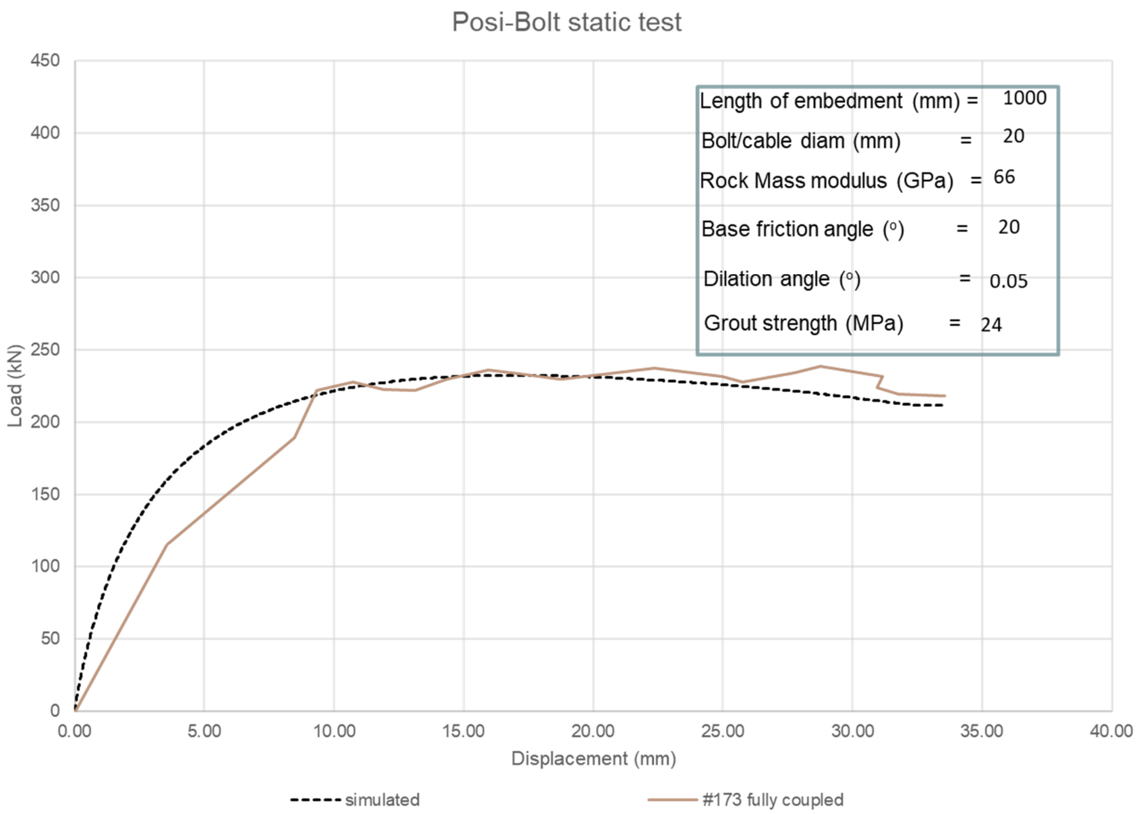


Figure 4 Simulation of the static test conducted on the Posi-bolt by WASM

Figure 5 Simulation of DSI Underground Posi-bolt tests with 1,000 mm of de-bonding conducted by WASM

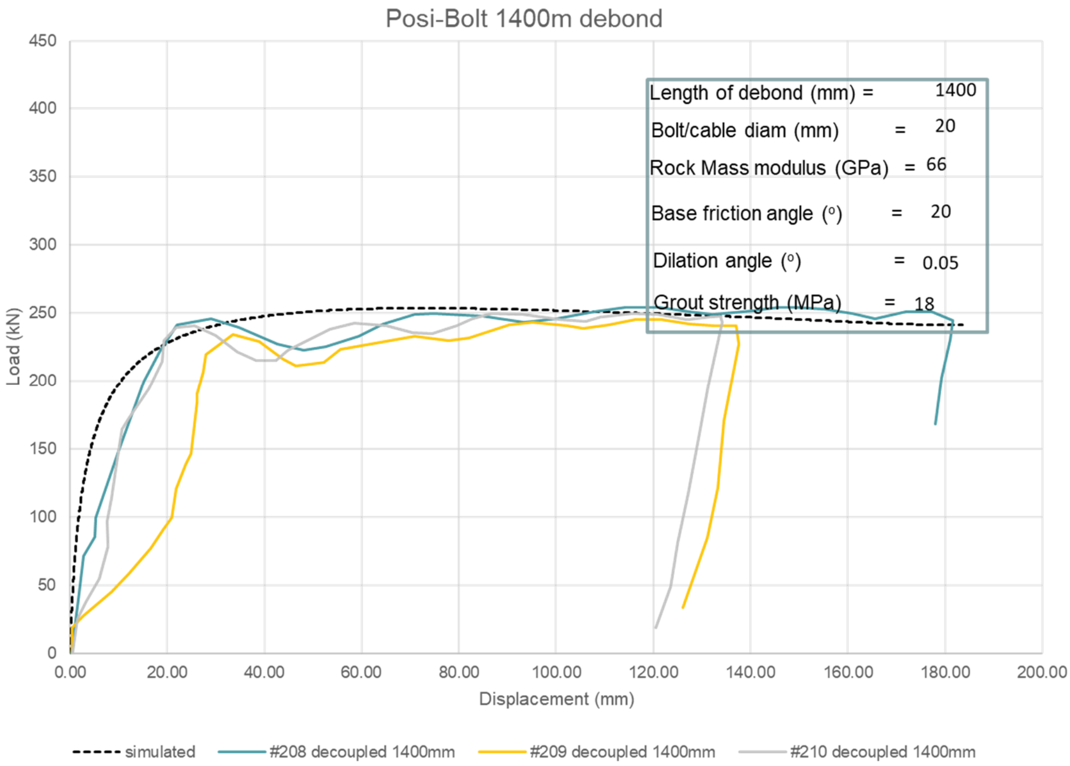


Figure 6 Simulation of DSI Underground Posi-bolt with 1,400 mm de-bonding

The main contention is that the response from a static test is replicated in the dynamic test except for the yield allowed by the de-bonded section. The next set of simulations were for tests in the laboratory conducted by Chen & Li (2015). Figure 7 shows the pull test on a D-Bolt and the simulation.

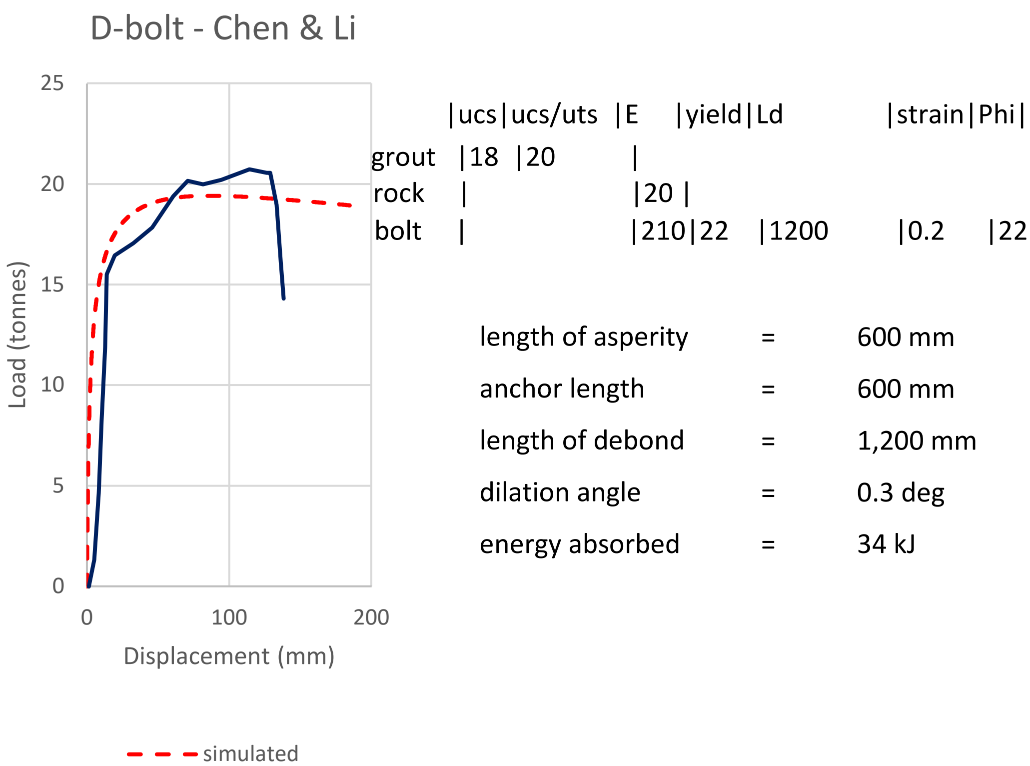


Figure 7 Pull test conducted on 22 mm diameter D-Bolt by Chen & Li (2015)

3 Rockbolt simulations: static tests and dynamic tests in the field

It is established that pull tests and shear tests in the laboratory can be simulated in dynamic and static modes. Can the same be applied to field tests?

So, to now consider what might be the response in a field situation, the initial consideration would be the rock mass modulus and the grout strength. The rock mass modulus may come from rock mass classification (in the author’s opinion, this is generally very conservative), or through conducting field tests (e.g. a dynamic test such as using the Sandvik/Epiroc method) and back-analysis or by conducting simple pull tests, which have been conducted successfully for several years.

Darlington et al. (2018) advised that, at one mine, the requirements were to provide an impact energy of 25 kJ and limit the displacement to 200 mm.

In order to determine the performance of the MDX bolt – under dynamic loading conditions – in situ dynamic testing was conducted at various mine sites.

The simulations and drop test results are shown in Figures 8 and 9, respectively, and indicate that the simulations are relatively good.

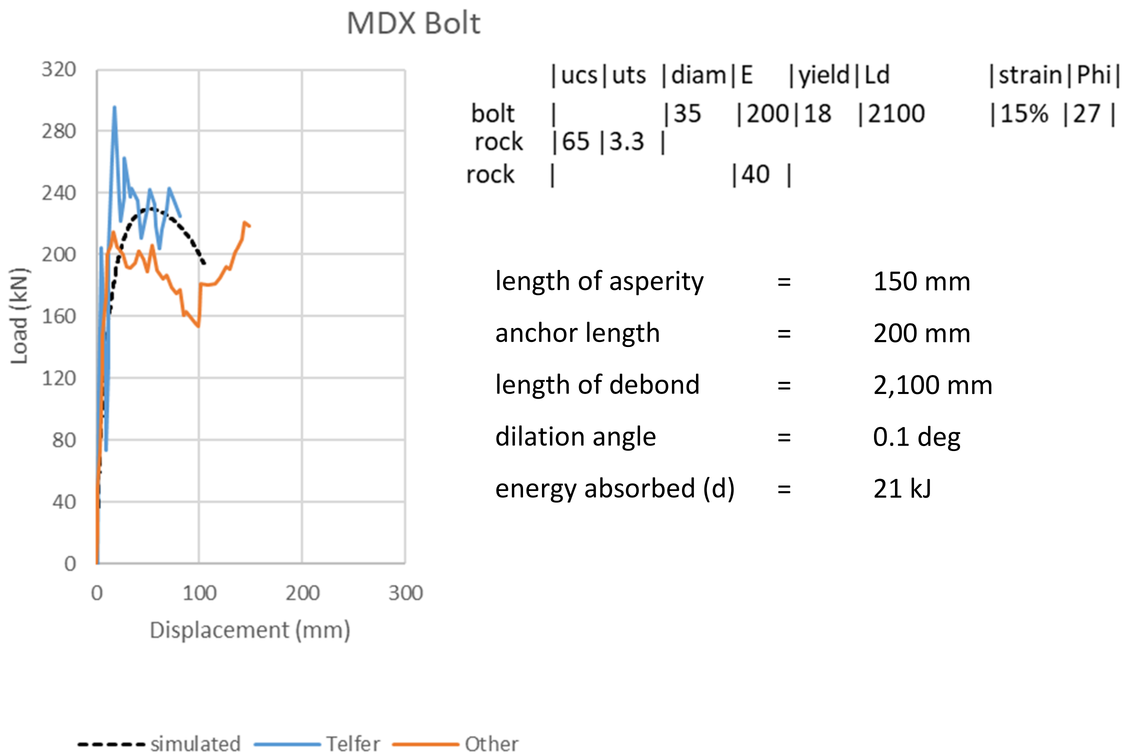


Figure 8 Dynamic simulation of the MDX bolt at Telfer (Darlington et al. 2018)

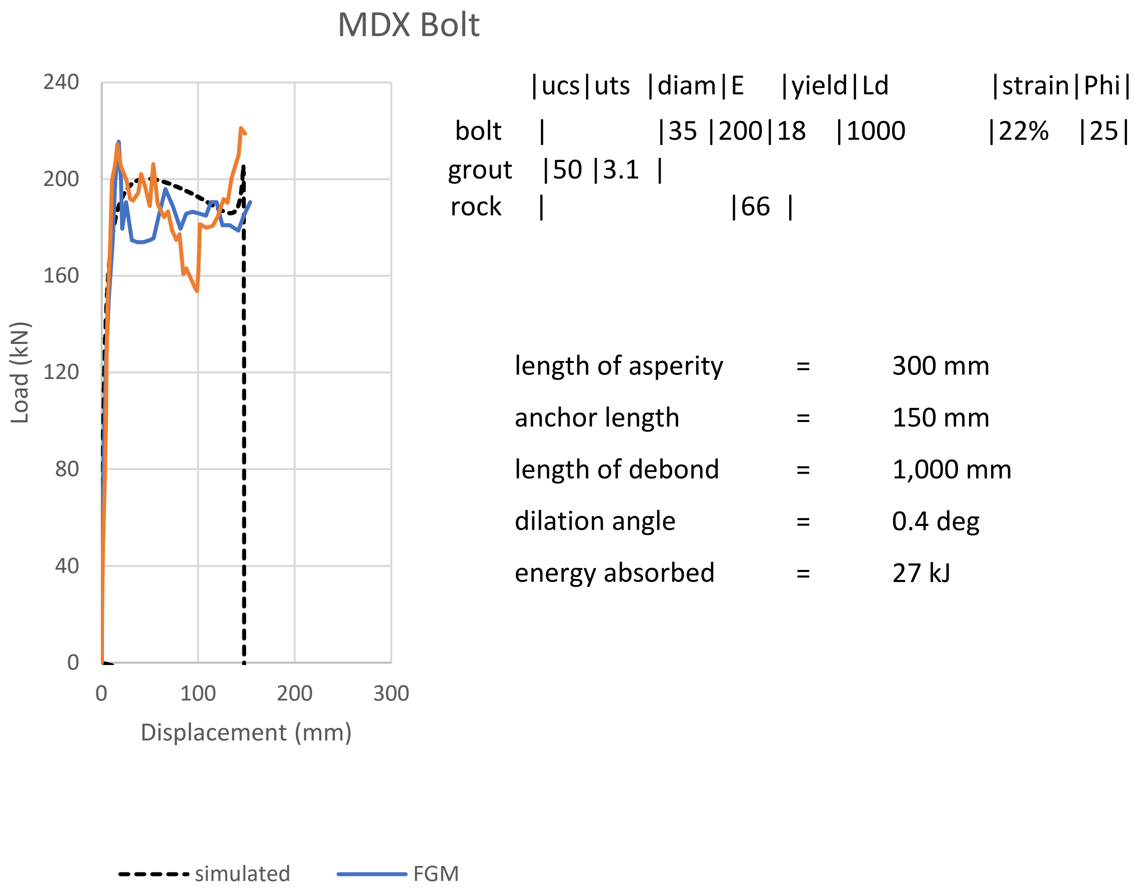


Figure 9 Results from a Sandvik drop test on 2,400 mm long MDX bolt at Fosterville Gold Mine

4 Developing design charts based on field testing for use in the field

A field approach was adopted for a study where the support system comprised used shovel rope as the proposed rock reinforcement. However, there was no laboratory testing to provide guidance.

The pull test result and the simulation result are shown in Figure 10.

The key parameters comprise a very soft rock mass (5 GPa), a low friction angle between the shovel rope and the grout (15°), and a grout strength of 27 MPa.

Once a simulation can be achieved, design curves can be developed, as shown in Figure 11.

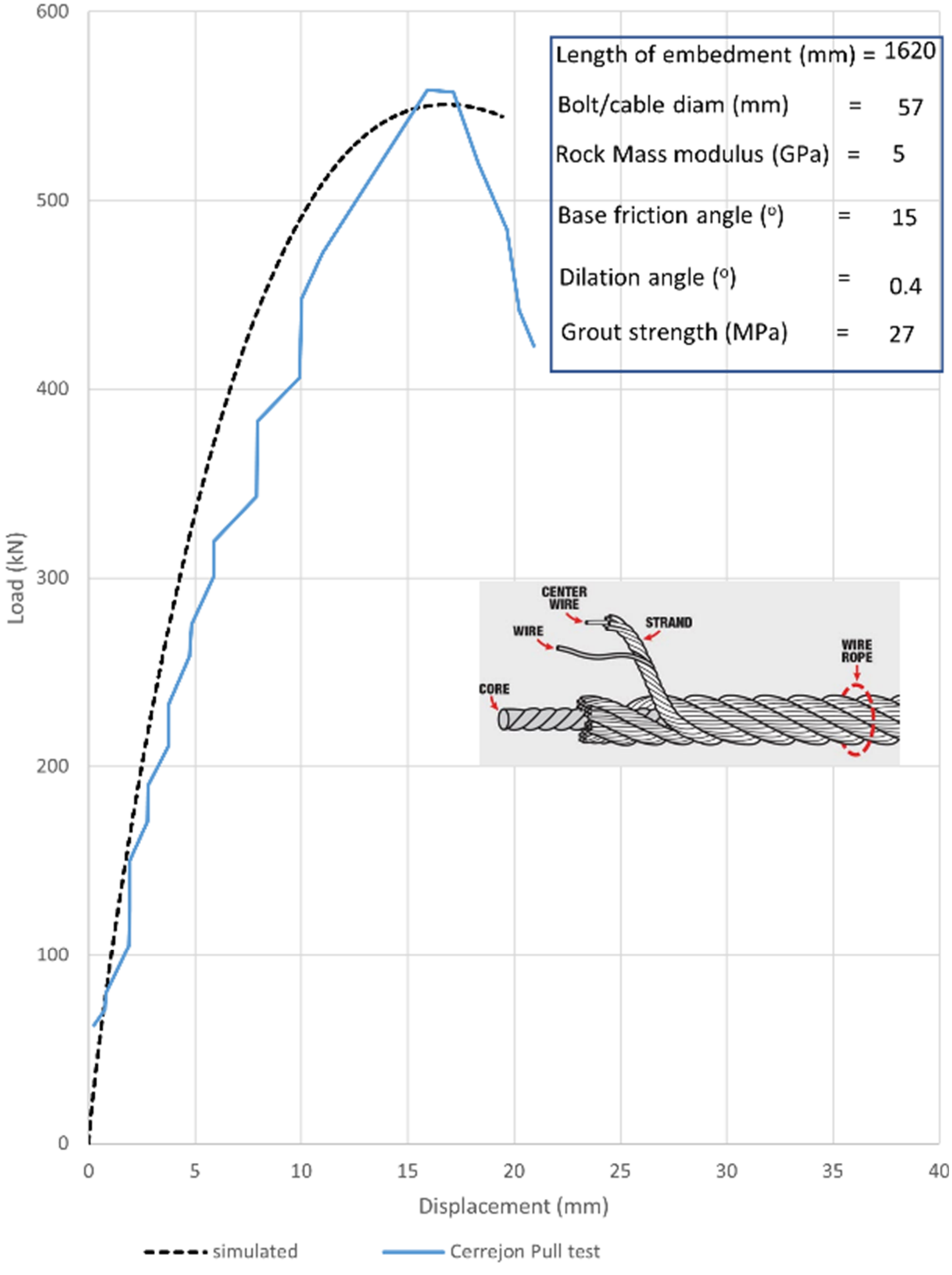


Figure 10 Pull test simulation for a 57 mm diameter shovel rope

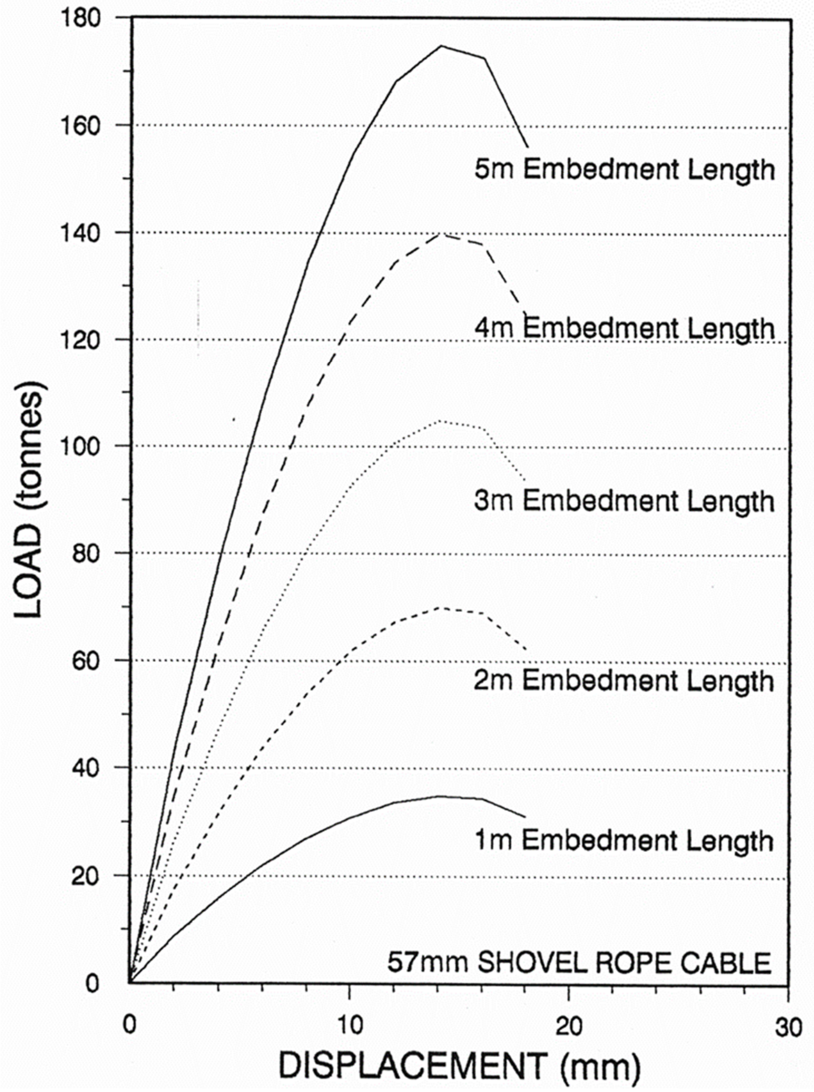


Figure 11 Examination of the influence of embedment length

5 Rockbolt simulations: static tests in the shear direction in the laboratory

As previously mentioned, there are several laboratories that can now also look at the influence of shearing. Laboratory testing of bolts in shear dates back to the 1970s (Dight 1985). An example of a shear test conducted in the laboratory by Chen & Li (2015) with a bolt aligned initially at 90° to the direction of shearing is shown in Figure 12. This figure depicts that the simulation for a bolt in shear at 90° to the applied load can be simulated quite well. For this simulation, the algorithm used was published by Dight (1985). Since then, the algorithm has undergone some modifications to allow for shear and tension.

Once shearing can be simulated, design curves can be developed, as shown in Figure 13. This figure depicts the influence on the shear strength of weakness planes influenced by shovel rope at different angles (70, 80 and 90°) to the direction for shearing.

The work described above was included in a paper by Jaramillo (1996).

One of the issues with the laboratory testing of static and dynamic properties is that the bolts are perfectly aligned to the applied load. This is obviously not the case in the field, and strainbursts can introduce shear on bolts because the bolts are not perfectly aligned to the direction of the applied force and the bolts will kink.

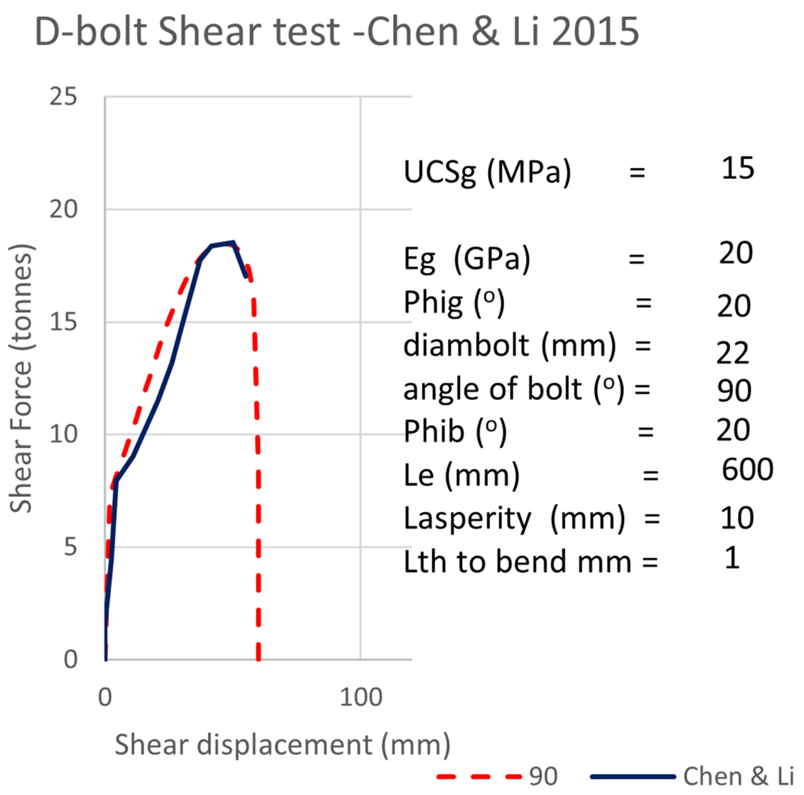


Figure 12 Shear test conducted by Chen & Li (2015) on a 22 mm diameter D-Bolt. The bolt was installed at 90° to the direction of shearing

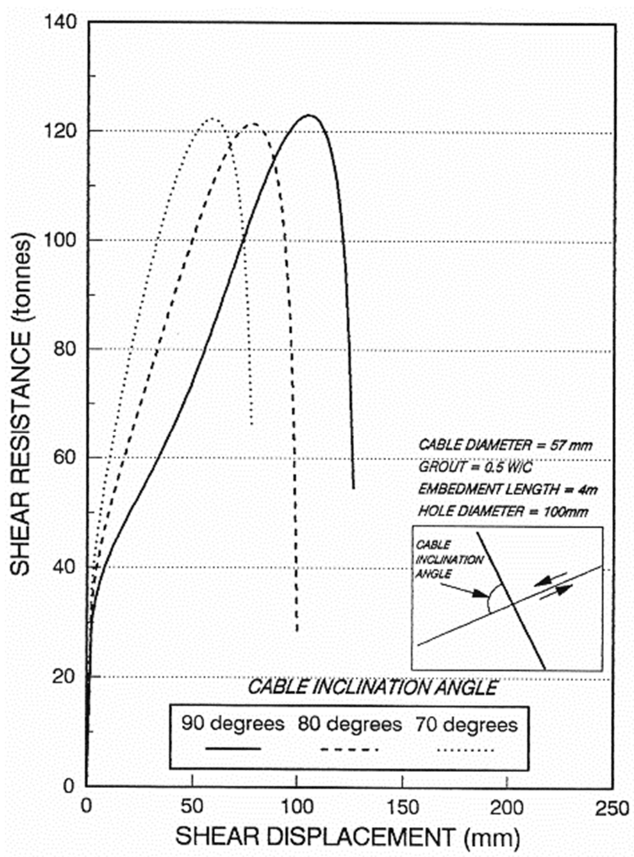


Figure 13 Examination of the shear strength of the 57 mm diameter shovel rope where the angle to shearing varies from 70–90° to the direction of shearing

6 Issues of quality assurance and quality control with grouts

What can be seen from the various simulations is the sensitivity of the bolt performance to the strength of the grout. Quality assurance and quality control (QA/QC) of cement grouts is common and mine sites often have a process for conducting this onsite. Although none of these tests appear to really look at the influence of the rock temperature on the set and cure (it affects shotcrete – Dight & Hulls 2009), the literature is silent on QA/QC of resin grout strength. There is also an additional challenge; the standard test (South African National Institute of Rock Engineering 2004) for resin grouts uses a 40 × 40 mm cube, so the stated strengths are not equivalent to the cement grout results obtained from 2l:1d cylinders. The resin grout should undergo a QA/QC process, but this appears not to be the case.

Work by Compton & Oyler (2005), and Varden (2005) and his colleagues undertook overcoring of rockbolts. The samples could then be visually inspected to ascertain the success of the grouting. A major issue relating to the plastic sleeve surrounding resin cartridges was identified where it had not been shredded, causing incomplete bonding of the bolt to the rock; called 'gloving' (i.e. the presence of the plastic capsule residue along the bolt).

7 Simulation of strainburst using bolt properties from pull tests

While it is important to be able to simulate the bolt response in the laboratory and the field, it is still insufficient to explain why the bolt system may be failing in dynamic/seismic conditions.

Observations undertaken by operations frequently identify the limited depth of failure to a seismic event. This depth appears to be about 10% of the minimum drive dimension, as shown in Figure 14. It is evident there are bolts left hanging after the clean up. These, however, were dynamic bolts. Could it be that in dynamic situations a combination of shear and tension on the bolt locks up the yield mechanism and the ground unravels to this depth? This observation is far too common, however, to be an isolated event.

A simulation has been conducted for a bolt installed where the crack location is 0.5 m behind the collar. The geometry of the simulation is shown in Figure 15. The bolt mechanical properties are those specified by the manufacturer. The plate deformation properties are as specified by the manufacturer. The grout bond strength has been obtained from a field test. The figure shows the distribution of the bolt load. It also shows the deformation, which is the critical element. As highlighted in Figure 16, there is a breakdown in this example of the grout–plate interaction adjacent to the collar, which would mean this system was not serviceable for the deformation experienced. A possible solution would be to ensure the grout goes to the collar, it has the strength specified, and that the load imposed by the ground on the plate is arrested with a stiffer plate. After all, it is the ground that needs to be supported.

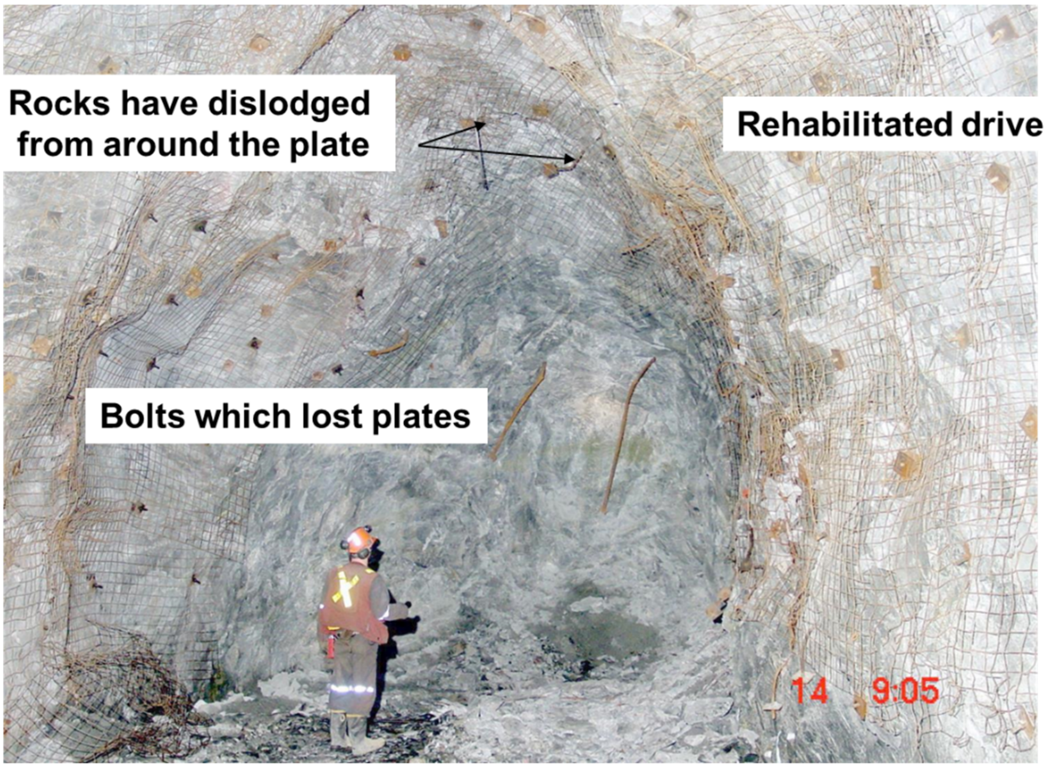


Figure 14 A drive showing the depth of failure following a seismic event

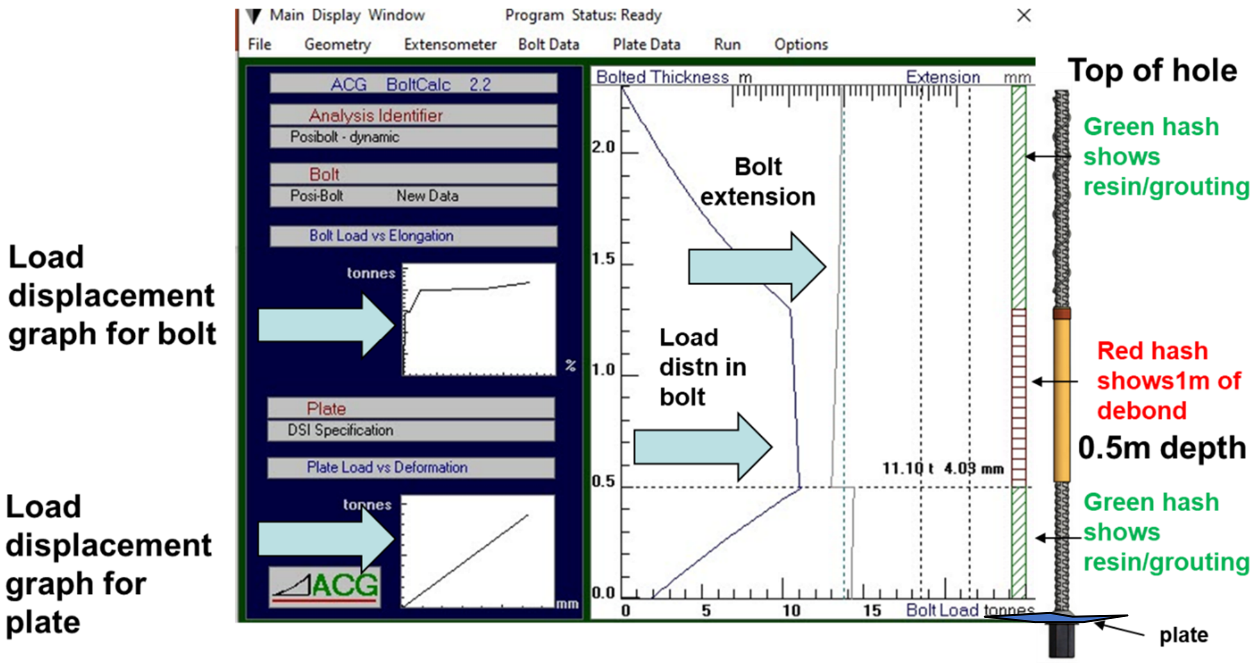


Figure 15 BoltCalc 2.2 analysis of the influence of a defect opening up 0.5 m from the collar (as in a strainburst). The software was originally developed based on concepts put forward by Fuller & O'Grady (1994) and adapted by the author

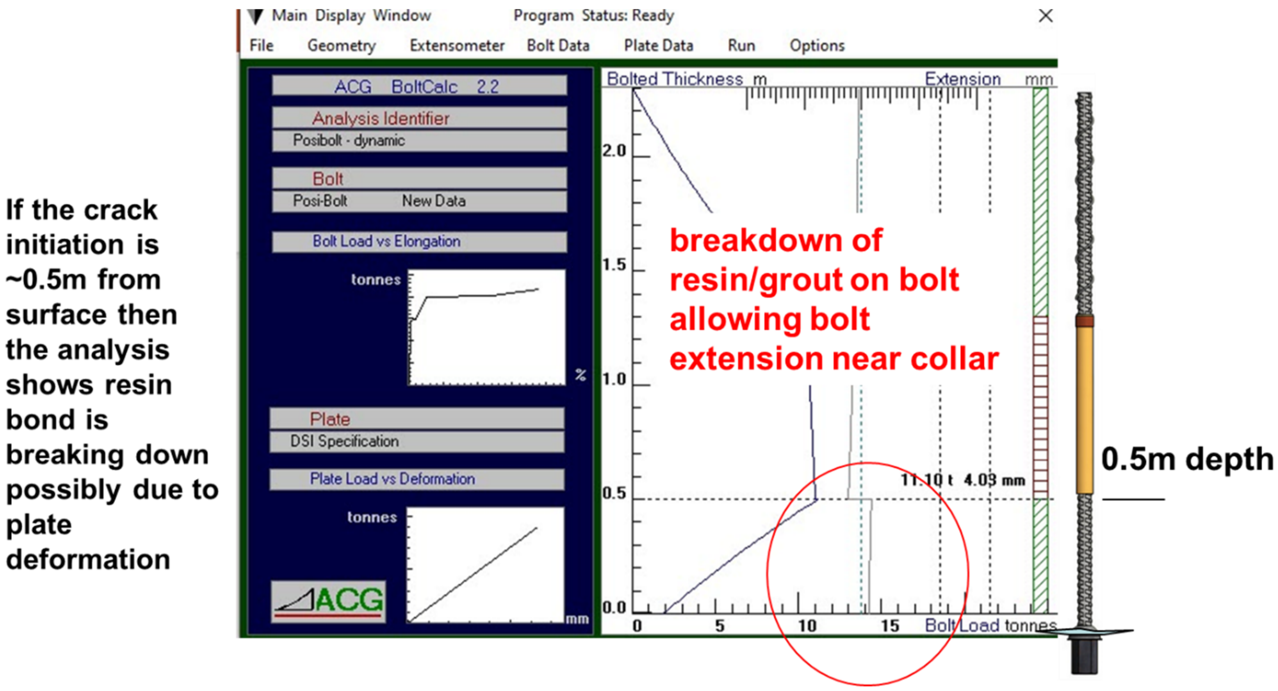


Figure 16 **Identification of a QA/QC issue that involves the bolt installation procedure, the grout strength and the plate response**

8 Conclusion

We have focused on the bolts and their properties. Dynamic testing is perceived to be the way to understand the energy absorption; although, as shown in this paper, the dynamic behaviour may, possibly, be an extension of the static behaviour. It has been recognised that field tests provide a different set of boundary conditions. It seems these can also be modelled.

The paper presents a different approach for assisting in the design of ground support systems. It is a very cost-effective and time-effective approach when compared to the traditional avenues of pull testing and drop tests. The simulations have been compared to actual test data to give confidence/credence in the results from the simulations.

It is possible to develop design curves from the simulations for actual (anticipated?) ground conditions for each mine site and lithology.

Observation of the impact of a seismic event suggests, however, there is a problem with the conduct of QA/QC of the grout and the bolt/grout/plate assembly.

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