The use of cable bolts or ground control—current applications and future innovation

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Chapter Outline

10.1 Introduction

Cable bolts were introduced to the U.S. mining industry in 1970 as a method to reinforce ground prior to mining. In the beginning, discarded wire rope was the preferred choice by most ground control engineers. Today, the basic cable bolt design consists of a high-strength, post-tension concrete (PC) strand that's installed in boreholes from 1 to 3-in. (25.4 to 76 mm). Cable bolts were traditionally anchored

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with neat cement, and still are today. Resin grouted cable bolting was introduced in the US coal industry in 1992 through research efforts of the US Bureau of Mines. The original work was conducted at a longwall operation in western Colorado for the purpose of finding alternative solutions for secondary tailgate and bleeder entry support (Tadolini and Koch, 1993). For the initial test, cable bolt design and installation were based on cable technology developed for the hard-rock mine industry (Goris 1990, 1991; Goris et al., 1993, 1994). This involved the installation of the cable by hand and using a fully grouted cable with a pumpable resin grout system. This technology was certainly adequate for the hard-rock industry but not for high-production coal mining operations.

From the beginning, the cable bolt system used today quickly evolved until an essentially new support product was created. The result was a cable fitted with a patented head that could be pushed through polyester cartridges and rotated rapidly to mix the resin and develop the strength of the PC-strand cable (Gillespie, 1993). Concurrently with bolt component designs, resin manufacturers were developing materials that required lower insertion forces and flow to penetrate the strands and "resin disruption" modifications required to increase cable bolt anchorage. Fig. 10.1 shows a cross section of a cable anchored with a polyester resin.

Cable bolts are commonly used for tailgate and bleeder support, entry and cross-cut support, and area that requires high-capacity bolting systems that can anchor above damaged or stress relieved zones. Cable bolts have even been effectively used in single pass longwall mining system, serving as both primary and secondary support (McDonnell, 2010).

The Australians had used cable bolts in both metal and coal mines as secondary support (Gale, 1987; Gale et al., 1987). Those cables are normally 33 ft (10 m)

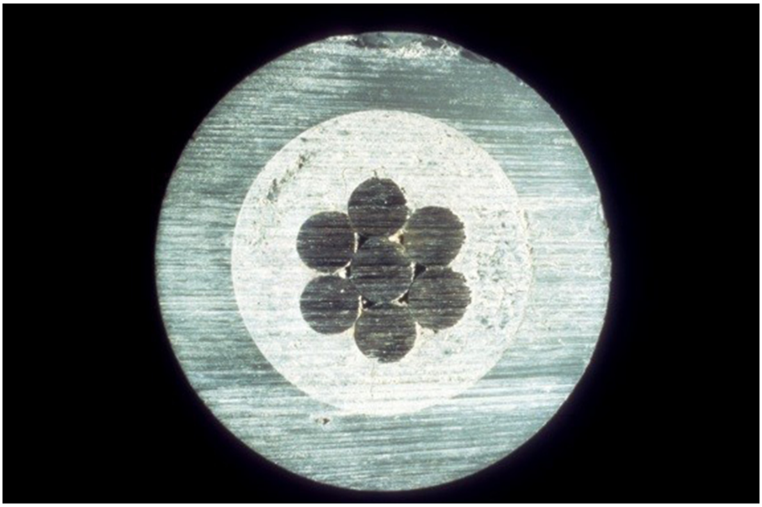

Figure 10.1 A PC-strand cable inserted into a 1-in. (25 mm) diameter steel pipe with a two component polyester resin (note how the resin flows around the individual strands).

long, fully grouted, and installed with a pumpable grout system. There have also been recent developments in cable bolting technology in Australia that will be discussed later in this paper.

10.2 Cable Bolt Design and Manufacturing

The cable bolts are manufactured from high-strength steel cables and are supplied in bright wire or a special galvanized coating to reduce corrosion. The most common cable used is seven strands 0.6 in. (15.2 mm) in diameter. The cable consist of six outer strands wrapped around a middle or king-wire. To manufacture the strand, individual wires are wound onto bobbins, shown in Fig. 10.2, where the machine pulls the center or king-wire while the outer strands are wrapped tightly around to form the final product as shown in Fig. 10.3.

The final cable is stabilized and wound onto individual cable packs that can be from 8,000 to 12,000 ft (2500 to 3750 m) long. Completed PC-strand cable packs are shown in Fig. 10.4.

The cross sectional area of the steel for the 0.6 in. (15.2 mm) cable is 0.217 in.^{2} (0.55 cm^2). But several diameters ranging from 0.5 to 0.9 in. (12.7 to 22.9 mm) are being used. Cable bolts can be any length but typically range from 8 to 20 ft (2.4 to 6.1 m) for use in coal mines and up to 30 ft (9.4 m) in hard rock applications.

Figure 10.2 Individual bobbins are lined up next to the machine that will feed into the winding machine.

Figure 10.3 The six outer wires are wrapped around the center or king-wire to form a seven-wire PC-strand.

Figure 10.4 Completed galvanized PC-strand cable packs, ready for bolt manufacturing.

Traditional cable bolts consist of a cable head that ties the cable strands together and allows the bolt to be installed and rotated with a roof-bolting machine. For ground control, the head is necessary for the ungrouted portion of the cable to accept load and resist rock movements via the bearing plate. The head is designed to permit the installation and “nesting” of a bearing plate or other surface control devices. The head is affixed to the cable using a barrel-and-wedge system that also allows rotation to thoroughly mix the two component resin as previously mentioned.

A stiffener is necessary to install the cable through resin cartridges with roof-bolting or hand-held equipment. Without the stiffener, the cable is too flexible to be pushed through the resin cartridges. With the new resins, the stiffener does not have to be as long as the resin column and field testing is required to determine the optimum length based on mining heights and equipment requirements. Another very important function of the stiffener is to protect the PC-strand from being nicked during the rotation and mixing of the resin. Any nicks in the strand can dramatically affect the cable capacity and subsequent performance.

Early field trials indicated that cable anchorage, particularly with larger diameter holes which increased the bolting annulus, would require “resin-interrupters” in the form of steel buttons, Garford bulbs, “bird-cages” (simply unwinding the strand) in the effective anchorage zone. Additionally, a steel button or other device had to be placed on the end of the cable to prevent unwinding during transportation, handling and final installation. The resin interrupters and end buttons also helped to mix the resin before serving as dead-point anchors after curing has occurred. Recent developments of indented PC-strand has also been very successful in anchoring resin grouted cable bolts and will be presented in more detail. Fig. 10.5 shows the configuration and components of a traditional resin anchored PC-strand cable bolt. The number and location of the anchorage bulbs can vary based on conditions and resin column length.

Alternate designs allow the cables to be post tensioned, similar to historical cement grouted cables, using a jacking system. This has been traditionally completed at the head of the bolt using a wedge-and-barrel head as shown in Fig. 10.6.

Tensionable cable bolts (TCBs) have also been designed to be installed using resin in-cycle with roof bolting equipment. The cables can be inserted, mix the resin, held until the resin cures, and then post-tensioned at the head, which places the bolt into tension while compressing the immediate roof. These systems provide lower installation cable bolt systems than hydraulic jacks, usually between 10,000 and 15,000 lbs (44 and 67 kN). These provide the additional benefit of one type of a single pass cable bolting system, serving as the primary bolt during development

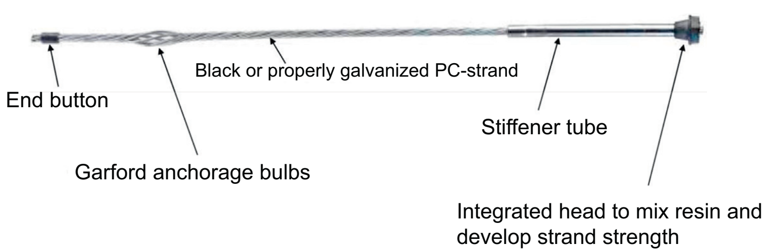

Figure 10.5 Key components of a resin-grouted PC-strand cable bolt.

Figure 10.6 Post tensioning a cable after installation.

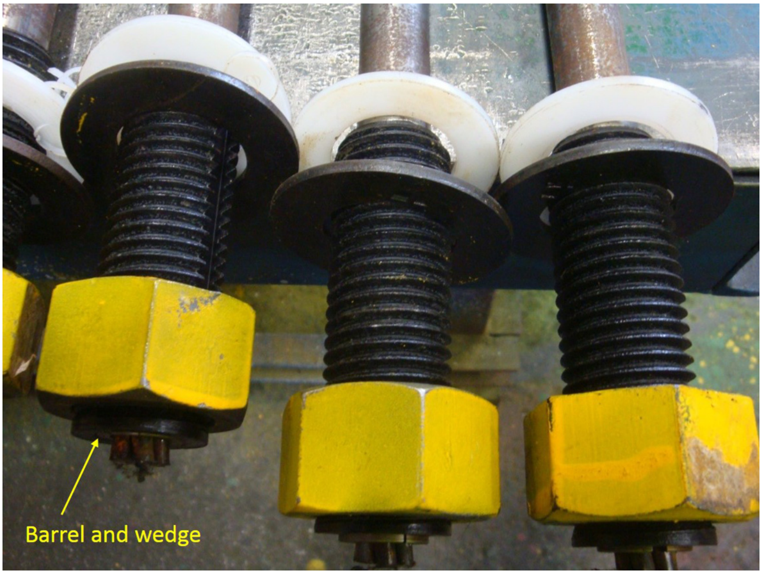

Figure 10.7 Tensionable cable bolts (TCB's). The yellow color designates the 10 ft (3.1 m) cable length (ASTM Standard F-432, 2013).

and as the secondary system while the longwall panel is retreating. The systems have also been used successfully in room-and-pillar coal mine operations and in several hard rock mines. Fig. 10.7 illustrates the TCB system and the critical design components.

10.2.1 Cable bolt characteristics and properties

Cable bolt strengths are based on the number of wires and effective area. For example a 0.6 in. (15.2 mm) cable manufactured from 270 ksi (1.8 GPa) steel, will normally exceed 58,600 lbs (260 kN). Larger diameter, multiple strand cables 0.9 in. (23 mm) can achieve 120,000 lbs (533 kN). The elongation of the cable at failure is largely dependent on the steel chemistry ranging from 3.5% to 8%. Cables will begin to yield and stretch at about 1% strain. When a cable is loaded, a single strand or multiple strands can rapidly dynamically fail, which is a traditional failure mechanism. There can be some load recovery from the remaining wires, but it is highly variable and will drop again when the remaining strands begin to fail. From anchorage testing, the elongation at failure is usually less than 4% strain (Barczak et al., 1996).

The stiffness of a cable will be determined by the free cable length in the hole and the elongation properties of the specific cable. However, some elongation in the resin-anchored section of the cable will influence stiffness and must also be considered. The deformation of a cable consist of three components: construction, elastic, and rotational elongation. Construction stiffness is permanent but usually very small. The rotational component is due to the rotation of the cable about the axis during a test of as the cable is loaded. The elastic component is dependent in part on the elastic modulus of the steel composing the cable. The elastic modulus of steel is 29.5 million lbf/in.^{2} (203.4 GPa). However, the elastic modulus of the cable is also dependent on the construction of the cable, which involves the lay length. The lay length is the distance on strand takes to make a complete revolution around a cable (Wire Rope Technical Board, 1985). The stiffness can also be calculated from the following equations:

$$K = \frac{E \times A}{L} \tag{10.1}$$

where K = stiffness, lbs/in. (kN/cm); A = area of cable, in.^{2} (cm^2) (true cross-sectional area); L = free cable length, in. (cm); and E = elastic modulus of the cable, lbf/in.^{2} (GPa).

Knowing the elastic modulus, length, and area, the cable stiffness can be calculated for an applied load. Cable stiffness has been measured underground using pull tests on cable installed in a limestone roof (Zelanko et al., 1995). For a 10-ft (3-m) cable bolt with a 5-ft (1.5-m) resin anchor and therefore a 5-ft (1.5-m) free length of cable, the initial cable stiffness below the system yield was 30.4 tons/in. (106 kN/cm) for cable installed in a 1-in. (25.4 mm) diameter hole, and 28 tons/in. (98 kN/cm) for a cable installed in a 1−3/8-in. (35 mm) diameter hole.

Based on these stiffness values, the deformation modulus of the cables can be calculated from the stiffness equations. However, a correction must be applied to the free length of the cable to allow for elongation of the cable in the anchor. From the load transfer characteristics and distances determined experimentally for grouted rebar, the elongation of the cable in the anchor can be approximated by an additional

8 in. (20 cm) of free cable length (Serbousek et al., 1987). Although the anchors will affect the load transfer, any error in determining the additional free cable length from the cable stretch in the anchor portion of the cable will only have a small effect on the stiffness calculations. From the example above, for the 30.4-tons/in. (106-kN/cm) stiffness, a free cable length 5 ft 8 in. (1.72 m), and an area of 0.217 in.^{2} (0.55 cm^2), the calculated cable modulus is 19.1 million lbf/in.^{2} (132 GPa).

Using the calculated elastic modulus and the stiffness equation, the stiffness of cable bolts with different free lengths can be determined. For a 14-ft (4.3 m) cable with a 4-ft (1.2-m) anchor and a 10 ft (3.0 m) of free cable length, cable stiffness would be 16.1 tons/in. (56.4 kN/cm). The assumption made is the anchor has sufficient lengths where the anchor will not slip and a portion of the anchor will have little or no load below the yield of the system.

The stiffness of the support will determine how quickly the support will develop resistance and load as the roof deforms. The cable bolt stiffness can be compared to the stiffness of other support systems and plays of role in the post-tensioning systems that will be discussed in more detail. For example, a 5-ft (1.5 m) long, 3/4-in. (19 mm) (No. 6), fully grouted rebar bolt, the stiffness is 200 tons/in. (700 kN/cm), and for a 6-ft (1.8 m) long, 3/4-in. (19 mm) in diameter point-anchor system, the stiffness is 50 tons/in. (175 kN/cm) (Karabin and Hoch, 1979).

So cable bolts have much less stiffness than most primary support systems. Although cables are more flexible, the lower stiffness indicates that they will not resist movement as much as other primary support for a given load. For secondary supports, a four-point poplar wood crib constructed 6 ft (1.8 m) high will have a stiffness of 21.5 tons/in. (75.3 kN/cm) (Mucho et al., 1999). This is equivalent to a cable bolt with 7.5 ft (2.3 m) of free length. However, in a tailgate support system, at least two or three cable bolts would be used in place of a single crib. In this case, the cable system would be two to three times stiffer than a crib.

10.2.2 Design concepts for cable bolting systems

Cable bolting system designs have evolved during the last 20 years for several applications that range from bleeder and tailgate entry support, long-term development entries, cross-cuts and intersections. And these design concepts are highly variable based on the installation of the cable, i.e., point-anchored, fully grouted, post-tensioned and tensioned as primary support. The most popular installation method ($\sim$90%) in the United States is point-anchored, where suspension is the primary roof support mechanism.

Original cable support designs were implemented to serve as secondary support. These supports were used to "supplement" the primary supports that were installed to withstand development mining and control the lower roof. The cable bolts were designed to maintain the immediate roof and prevent it from falling, keeping the entry open during all phases of mining. As the lower roof moves and deforms, the cables distribute the forces that develop below a given support failure horizon deeper into the roof through the cable and anchor support. Although there is primary support, it is not normally taken into account when designing cable support systems that act as suspension mechanisms. This is quite common for the analysis of secondary support, including standing supports (cribs and cans) and truss systems.

The basic concept in using partially grouted cable bolts to support the roof's suspension. Essentially, the cable bolt system must maintain and control the dead weight of the rock or rock movement below a potential failure horizon or inherent weakness in the immediate mine roof. This part determines the number and spacing of the cable bolt systems. Additionally, an adequate cable anchorage length must be developed above the suspected failure horizon, to ensure that the capacity of the cable is obtained without a failure in the anchorage zone. Experience based on numerous test sites in tailgate entries have further refined and established basic designs for cable row and spacing along the entry. Although the cable systems are designed for the full dead weight of the rock, this is seldom the case and is an over simplification of mining conditions, but does present the "worst case scenario." Also lateral roof movements, vertical expansions from movements, and shear zones across and through geological anomalies can cause loads to develop beyond the dead-weight of the supported rock.

10.2.3 Cable length

The selection of the cable length is the most critical aspect of the design of cable support systems. Depending on the geologic conditions, selecting the length may be simple and straight forward, while in other cases it may be an iterative process with a wide range of variables. Difficult and complex conditions may even require test areas to ensure the cable length and spacing are adequate to control the immediate and main roofs.

Once the deepest potential failure horizon is identified, the cable length will be the depth of this failure horizon plus the length of the required anchorage length to develop the installed cable capacity. Typical cable bolt lengths in gate roads are between 12 and 16 ft (3.7 and 4.9 m) while cables shorter than 8 ft (2.5 m), for any application, defeat the benefits of the system and alternative traditional steel bolts should be examined. The cable bolt length should ensure that the anchorage zone is at least partially above the primary support anchorage zone. In this case the primary support zone is being suspended by the cables. However, there may be failure planes that develop above the primary support zone and require a longer cable bolt. The observed potential failure zones are traditionally arched or flat in sedimentary deposits, depending on how the roof may fail. In longwall gateroad systems, much deeper roof movements may occur due to the caving action of the immediate and main roof systems, but they are not relevant to the stability of the immediate roof or opening.

The initial step in designing an adequate support system requires gathering detailed information on ground conditions and the underground mining environment. To determine a potential failure horizon will require examining the roof and roof geology. The information may include a general estimation of the rock mass strength of rating, geological structures, and strengths of the immediate and main roof members. This information can be obtained from core hole samples and supplemented by borehole cameras to evaluate changes and identify geological transition zones. If the rock overlying the immediate roof is stronger or more competent, this may be an obvious place to locate the anchorage zone and is the easiest designs to determine. If the geology is not continuous or not clearly defined with a competent anchorage horizon, actual mining experience, test sites, and examination of ventilation overcast and roof falls can provide more data to help design the cable support system. Test sites that utilize basic instruments, such as multiple position sag stations or extensometers can also be used to identify weaker zones in a laminated roof. Instrumented test sites can be used to confirm, modify, and optimize the adequacy of a cable length and spacing designs.

10.2.4 Suspension designs

For cables, to consider that the rock is being support through suspension may be an oversimplification, but does provide a basis for establishing the initial design requirements of the system. Designing for suspension requires that the cables carry the weight of the rock under the potential failure zone, which, in many situations, is the worst-case scenario (McDonnell et al., 1995). In some situations, there will be loads that actually exceed rock load or movement, and mining induced loads.

For suspension, the simplest approach is to identify a parting or plane or a flat-lying, potential failure surface above the bolted roof horizon where the roof will shear the pillar edge of the opening and the entire weight of the rock must be supported as a detached block as shown in Fig. 10.8. The weight of the material can be determined using the following equations:

$$F_w = W_e H_p \gamma \tag{10.2}$$

where F_w = weight of rock per linear length of entry, lbf/ft (kN/m); W_e = effective width of the opening, ft (m); H_p = distance from the entry roof to the parting plane, ft (m); and γ = rock density, lbs/ft^3 (kN/m^3).

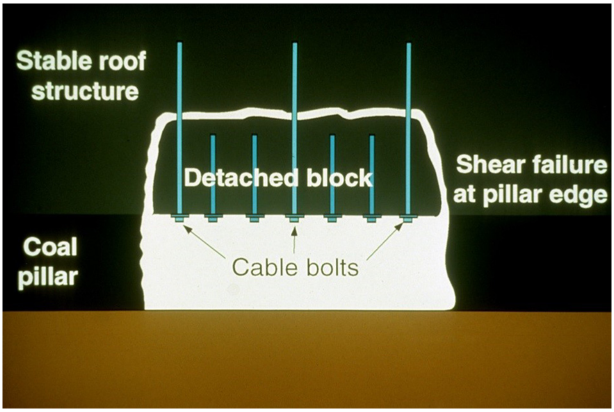

Figure 10.8 Detached block of a failed roof supported by cable bolts.

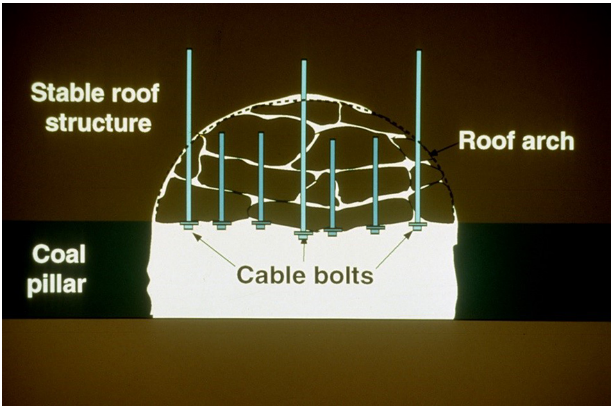

Figure 10.9 Formation of a pressure arch of failed mine roof.

If an arched roof failure is formed with the pillars carrying some of the weight, the cable need only support the weight under the arch (Fig. 10.9). The height of the arch will be determined by a combination of the geology as well as by the vertical and horizontal stresses acting on the roof that generate the induced mining stresses. The length and number of cables will depend on the height of the arch, and therefore the identification of the failure surface is very important. The weight of the material within the arch can be estimated from the following equation:

$$F_a = \frac{\pi}{4} W_e H_a \gamma \quad (10.3)$$

where F_a = weight of the rock under the pressure arch per linear foot of the entry, lbs/ft (kN/m) and H_a = height of the pressure arch, ft (m).

The behavior of the pillar under different loading conditions will affect the width of the opening and therefore the weight of the rock that must be supported. The depth of the yield zone can be determined using underground observations or estimating it using equations that were developed by Wilson and depend on the strength of the coal, roof, and floor material (Wilson, 1972). This is the mistake that inexperienced ground control designers often make. As shown in Fig. 10.10, the yield of the pillars and/or longwall panel has a direct impact on the effective width of the opening (W_e). The effective width needs to be used in the suspension and arch calculations to ensure that enough cable capacity is available to support the weight of the failed rock.

10.2.5 Design case studies

When using cable bolts for secondary support in longwall tailgates, there are three distinct zones that must be considered in evaluating the design and performance of the cable systems. These zones are the outby abutment loading zone for both vertical and horizontal stresses, the shield zone from the face to the back of the shield,

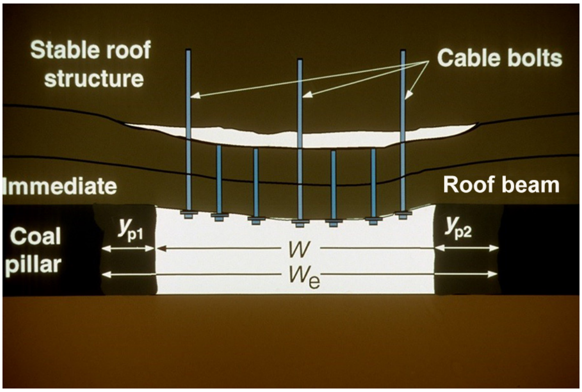

Figure 10.10 Formation of the yield zones and the effective entry width (W_e).

Figure 10.11 Tailgate abutment zone outby the face support with cable bolts (note the pillars are already sloughing on both the pillar (right) and coal panel (left)).

and the cave zone created after the longwall coal block is extracted. Each zone has different performance requirements, and therefore, the cable system must be designed to meet these requirements. If problems do occur in the tailgate that result in the shutdown of the longwall, they can be costly from an operational perspective but more importantly, dangerous to remediate and correct.

In the forward abutment zone, the cable supports must maintain an open tailgate entry and prevent any major roof falls that impede the use or access of the tailgate as a secondary escapeway and required ventilation as shown in Fig. 10.11. In the abutment zone, the cable loads will depend in part on the geology, mining depth, entry width, cable spacing, and pillar designs. This zone receives support from the pillars and the panel and may extend up to 150−200 ft (45−60 m) wide. The depth will control the yield zone that develops along the tailgate entry, which will increase the effective roof span as discussed in the design section. This yield zone will obviously increase as you approach the longwall mining face and remove the support of the coal panel. With pillar designs, abutment sized pillars will offer the most support to the tailgate entry. With a yield pillar adjacent to the tailgate, significant roof movements and cable loads can be realized. This example illustrates a "cribless" tailgate where no additional standing supports have been installed. The entire longwall panel loading can be properly managed by using cables bolts. In this design, four cables, 16 ft (5 m) long on a 5 ft (1.6 m) row spacing were installed between the rows of primary roof support.

In the zone from the face to the back of the shields, performance requirements are very similar to those for the abutment zone—the area must remain open as an escapeway and for ventilation. However, the support provided by the coal panel have been removed and replaced with longwall shields, and this creates an opportunity for the roof to move because of the loss of support. Therefore, higher cable loading will be realized and this is the mining phase that the supports should be designed. As shown in Fig. 10.12, the longwall shear has removed the coal and the shield has been moved forward to support the face area. The roof area between the longwall shields and the adjacent pillar should remain open for the required ventilation stand times, usually one intersection crosscut behind the face.

Figure 10.12 Longwall tailgate entry adjacent to longwall shields (note the failed rib and panel materials on the mine floor). The worker is standing in the tailgate entry underneath cable supported roof.

10.2.6 Designs for lateral movements

A common loading condition in mining applications is lateral movements that are created when longwall coal blocks are removed by the shearer. Cable bolts will offer resistance to lateral movement, although shear is resisted to a large degree only after the peak rock strength has been exceeded. Essentially the rock has failed and is now mobilized where the cables will offer significant post-failure resistance by significantly increasing the residual shear strength of the rock (Goris et al., 1995). However, in some instances, because of the large lateral deformations, the cables may not be able to stop or limit this displacement prior to failing. At a mine in Colorado, a tailgate supported with cable bolts was subjected to large horizontal movements and lateral displacements. This occurred as the adjacent panel was being mined, with the horizontal stress abutment causing roof damage not only to the headgate entry, but also to the tailgate of the next panel through the crosscuts (Dolinar et al., 1996). This panel was supported with cable bolts and rigid trusses. At approximately 1−1.5 ft (0.3−0.45 m) of lateral movement occurring in places along the entry, the rigid truss cross bars have been thrown from the angle bolts and about 20% of the cables had failed in tension. It was estimated that the cable withstood about 2−4 in. (5−10 cm) of lateral movement before failure. These are very difficult ground conditions where a few support systems could be expected to prevent movements of this magnitude. With shear and lateral movement, the flexibility of the cable bolts are not fully utilized. Fig. 10.13 illustrates high horizontal movements being controlled by cable bolting systems.

Figure 10.13 The roof is “folded” as illustrated in the bent heavy roof mats from the lateral movements and shear loading. The cable bolts installed in the mats are intact and continue to support the failed material.

10.3 Tensioned Cable Bolting Systems

Cable bolt designs would be incomplete if tensioned systems were not included as part of the discussion. Pre-tensioning rock and cable supports, whose benefits have been debated for years, has become common in the underground mining industry (Gray and Bates, 1998; Frith and Thomas, 1998; Lawrence, 1998). Combinations of low-friction nuts that develop high torque-tension ratios and hydraulic jacking equipment to apply pre-tension loads to bolts and cables has been investigated by these authors and several other prominent researchers. It is very important to have an understanding of the fundamentals of bolt tension theory and then compare those results with actual field data and subsequent performance.

10.3.1 Tension cable bolt discussion

Pre- or post-tensioning cable or roof bolts creates an active force on the bearing plate, which is intended to provide improved support performance. The key component for the successful application of this pre-load to the bearing plate is to be able to transfer active forces into the roof while maintaining or increasing confinement. Of course, this is dependent on the stiffness of the bearing plate, which should always be as strong and as stiff as the installed roof support system.

The justification for pre-tensioning roof bolting systems is typically explained using the theory associated with concrete beams. A review of structural mechanics reveals that pre-tensioned concrete beams are always kept in compression by the applied forces that allow the beams to withstand high degrees of bending without failing. Unfortunately, the beams we have to work with in underground mining environments, if any, are not uniform in thickness, homogeneous, isotropic, and composed of a linear elastic continuum. In fact, even a uniform uniaxial state of stress is not likely to exist. Actual field measurements report a complex rotation and changing of three-dimensional stresses from one side of the entry to the other during the different phases of mining. Structural design codes indicate that mechanisms when a beam fails axially are a combination of buckling and material failures. If a beam were successfully created in a mining environment it would be nonuniform in thickness, highly variable in structural integrity, and contain geological materials with a range of physical properties, i.e., Young's moduli and Poisson's ratio. Additionally, roofs associated with high degrees of loading and deformation can have a high lateral stress across the roof line. When these areas are examined, compressive and tensile failures resulting from localized shearing along the lines of discontinuities can always be observed. When you consider that most mine roof rocks are 10 to 20 times stronger in compression than in tension, when determined from intact rock samples and even greater when considering rock mass strengths, you begin to understand the importance of controlling downward deflections and movements. These types of actions can cause tensile failures in the immediate weaker roofs.

10.3.2 Applied roof loads

When a cable bolt is tensioned the forces are transferred into the roof through a competent bearing plate. One method used to evaluate these relationships is specified in the Boussinesq equations. These equations have been defined and used in civil and geotechnical engineering applications for decades. The original work stated that it was applicable for materials that are homogeneous, isotropic, linear elastic mediums. As previously stated, these conditions do not exist in underground mining applications but will still provide some insight into the rapid dissipation of applied forces under ideal circumstances.

To estimate the vertical pressure at a depth above the immediate roof line exerted by applying tension to a bolt, which exerts an applied load to a bearing plate, the following equation can be used (Terzaghi and Peck, 1948).

$$P_{\mathrm{v}} = 3Q/2 \times \pi \times z^2(1+(1+(r/z)^2))^{2.5} \tag{10.4}$$

where P_{v} = calculate pressure at any point, psi (MPa); Q = applied vertical load, lb (kN); π = constant, 3.1415; z = depth or vertical distance from the point of application of Q, ft (m); and r = horizontal distance from the point of application of Q, ft (m).

The dissipation of applied load with depth is shown in Fig. 10.14. In this example an applied load of 40,000 lb (17.8 kN) has been applied to a square 6 in. (15.2 cm) bearing plate. It can be seen that the induced stress at four times the length of the bearing plate or 24 in. (60.9 cm) is less than 5000 psi (37 MPa) or about 12.5% of the applied force. As shown, the force or stress applied to the roof of the rock mass rapidly dissipates.

A caveat to this theory is that it does not account for any separations or partings closed by the applied tension, especially within the primary support roof-bolting horizon. This may have a dramatic effect on re-establishing or stabilizing a competent layer of immediate roof material.

Some Australians have promoted cable bolt pre-tensioning as a "requirement" for adequate roof control. Most of their findings are based on field measurements and actual performance; the results have been impressive. In fact, Frith states, "It is noted with great interest that this basic finding is very difficult to substantiate using traditional rock mechanics theory but is readily understandable when proven structural engineering principles are applied to the problem of coal mine roof behavior and control" (Frith, 2000). The presented field results are difficult to argue. They show less roof movement and often "buy" longer stand times with the same diameter and length of bolts in a tensioned and nontensioned state.

If we use the same example discussed above using structural engineering principles and place a single tensioned cable, or even a rigid bolt, with a 12.8 ft (4 m) free length on a 6.4 ft (2 m) row spacing and apply the 40,000 lb or 20 tons (178 kN) of load, the effective resistance against horizontal stress increases within the height of the buckling roof. The results is (40,000 lb × 200 (mechanical advantage))/12.8 ft/6.4 ft = 661 psi (4.9 MPa). Essentially, this means that a cable installed and tensioned before the roof begins to dilate at the density of one cable

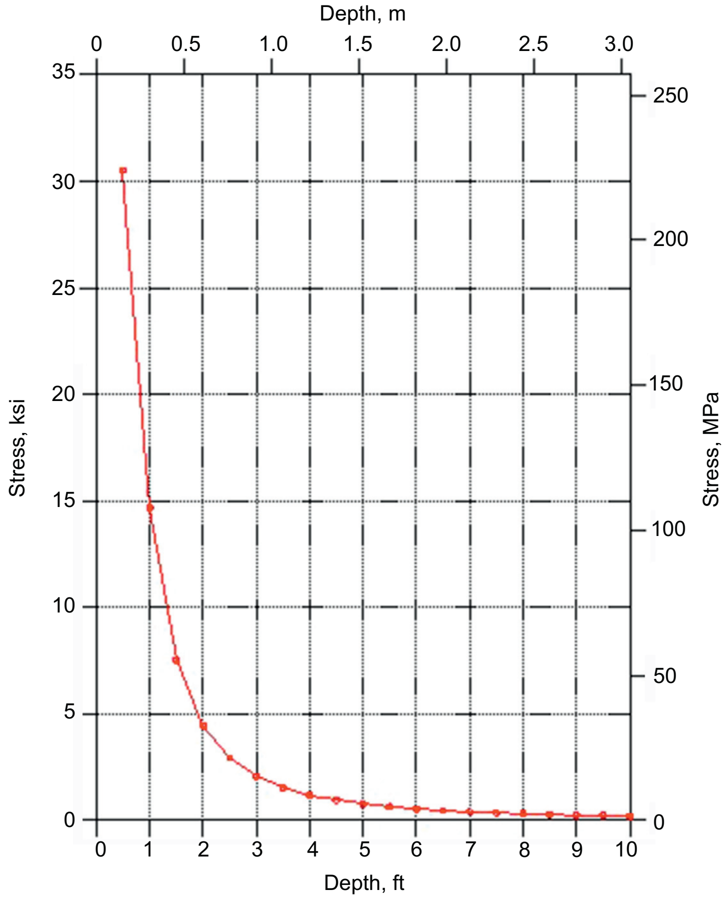

Figure 10.14 The dissipation of an applied load of 40,000 lb or 20 tons (178 kN) with depth into the mine roof.

on a 6.4 ft (2 m) row spacing in the middle of the entry, tensioned to 20 tons, offers an active resistance of 661 psi (5 MPa) to any horizontal stress increases that may occur within the first 12.8 ft (4 m) of the roof. This is actually a very significant resistance and does not include the passive resistance of the cable if roof movement occurs and inherent buckling resistance within the roof itself.

When you examine installed bolt tension (roof compression) with shorter and lower capacity fixtures, such as resin assisted bolt; the picture becomes even more clouded. Yassien et al. (2002), argue effectively and present cases that compare fully grouted resin rebar and tensioned rebar roof bolts. They determined that the most important characteristic was the bolt stiffness that is created by the full contact with the surrounding rock mass along the entire length of the bolt. In fact, they conclude that fully-grouted bolts can significantly alter the stress distribution within the bolted horizon because of the increased stiffness. The installation of highly tensioned roof bolts only altered the state of stress about 3 in. (75 mm) at the bottom of the bolt and 1.8 in. (45 mm) at the top of the anchor. Because the resin bolts deform together with the host rock, it is effective in resisting both the axial displacement in the bolted roof strata and shear sliding along the bedding planes. Due to its stiffness, the resin bolts maintain considerable vertical stress with the bolted strata to provide vertical confinement, making the roof stronger and better able to resist downward motion and horizontal stress.

It is important to remember that the installed tension could close cracks and separations with the first 23.6 in. (60 cm) of the immediate roof, enhancing the roof integrity. The creation of these compressive zones will also increase the intact rock strength and improve the stability of the roof.

While pondering which argument is correct, the authors believe that a combination of both concepts would be advantageous to develop and apply to bolting systems that can be tensioned while providing the benefit of system stiffness. Tensioned rebar systems meeting this criterion have been successfully used globally to support challenging roof conditions. The system utilizes a fast resin at the top of the bolt and a slower resin on the lower portion. When the fast resin has cured, the bolt is quickly tightened before the slow resin reacts and encapsulates the remaining lower portion of the bolt. Tension rebar systems can be applied up to 1 in. (25 mm) in diameter but are usually restricted to about 8 ft (2.5 m) in length.

The challenge is to suspend and reinforce the mine roof that has yielded above the primary bolted horizon by installing long cable systems that can offer the benefit of a tensioned and fully grouted system. Cable units have been developed that utilize jacking systems that are subsequently post-grouted to increase the system stiffness. A major disadvantage of these systems is the cost and labor required to install the units, but just as important is the timing of the installation. These systems are often installed long after the primary mining and support cycles have been concluded thereby allowing the roof to move from the elastic portion of the ground reaction curve to the yield portion of the curve where you are simple "hanging" failed material and not helping the roof to become "self-supporting" with your support system.

What would be more practical from an operational, as well as a ground control, perspective would be to install the cables with a two component or speeds of resin grout and tension the system before the bottom portion has cured. Mechanical systems have been recently developed that can be installed up to 15,000 lbs (66.7 kN) of tension that have special features that prevent "wrapping" or twisting the cable during the tightening process as shown in Fig. 10.15. The previous disadvantage of this system is that the insertion of the cable through enough resin proved difficult because of the flexible nature of the cable—an advantage for roof movement but a disadvantage for insertion pressures, which is analogous to pushing a rope up into a long hole. Expansion shell systems installed up the axis of the bolt or at the top may tighten the bolt up to the levels of the shear strength of the rock mass at the shell leaf interfaces. However, if the expansion shell is not fully encapsulated in resin, when the cable loads from the bottom and the shear strength is exceeded, the roof can drop down rapidly and any confinement may be lost. The roof can become broken, hazardous and fall in-between the remaining intact supports.

Figure 10.15 Tensionable cable bolt with nonrotation sleeve installed with a pressure pad to determine initial and subsequent loads.

Resins with the correct viscosity and gel times have been developed that allow the operator to install the cable, mix the resin thoroughly, and then tighten the cable bolt from top to bottom using the large column of resin at the top to become the anchorage point. The slower setting resin at the bottom can then "lock in" the bolt tension and keep the microfractures and roof bed separations held tightly together—which is a result of system stiffness.

10.4 Indented PC-Strand Cable Bolts

New technology in strand design has resulted in an innovative process to anchor the PC-strand bolts and effectively transfer the loads back into the rock mass.

10.4.1 PC-strand design and testing

PC-strands are traditionally seven-wire configurations, where the king wire or center wire is wrapped or covered with the remaining six outer wires. While it can vary by design, the king wire can be slightly larger in diameter to ensure the outside wires contact each other. A process was developed to indent the individual wires before they were wound in the final stranding process. These indentation patterns were refined using numerical simulation and finite element modeling and are analogous to the deformations on traditional steel rebar bolts or rods. The deformations,

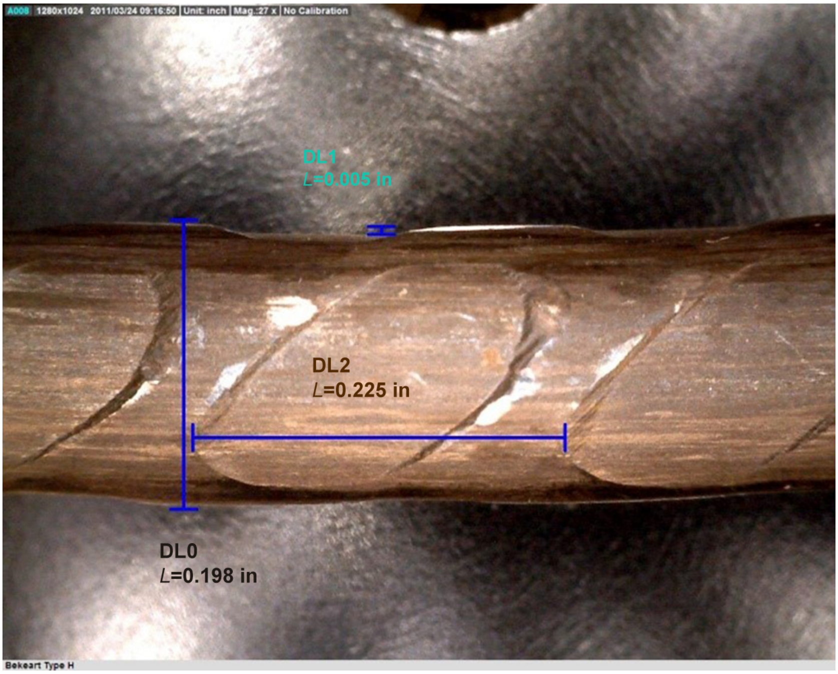

Figure 10.16 An individual indented wire under magnification—note the vertical ridges where resin or cementitious material can form locking mechanisms.

along the entire length of the cable, provide irregularities in the strand to form mechanical interlock features which can improve anchorage and enhance stress transfer from the cable bolt to the rock mass. A sample of the indented PC-strand under magnification is shown in Fig. 10.16.

Complete laboratory testing protocol and results can be found in Tadolini et al. (2012). The laboratory anchorage testing results are shown in Fig. 10.17. The regular or "smooth" PC-strand averaged 19,795 lbs (88 kN) before being pulled out of the steel pipe. The open cord, "L", "S", and "H" averaged 19,250 lbs (86 kN), 23,700 lbs (105 kN), 34,440 lbs (153 kN), and 37,500 lbs (167 kN), respectively. The "H" samples indicated an 89% increase in anchorage capacity versus the smooth, conventional PC-strand cable. Open cord cables are created by using a king wire with a large diameter that prevents the outer or strand wires from coming into contact to the adjacent wire thereby leaving rooms for resin to flow around the wires. The designations "L", "S", and "H" are indentation heights: low, standard, and high.

While anchorage is an important indication of load capacity, a significant parameter is the system stiffness of the cable and the resin. In this case, the stiffness is characterized by the amount of force (lbs) is required to move the cable a known distance from the pipe (inches). The regular strand resulted in an average stiffness of 33.25 tons/in. (116 kN/cm), and if we compare that with sample "H", which had

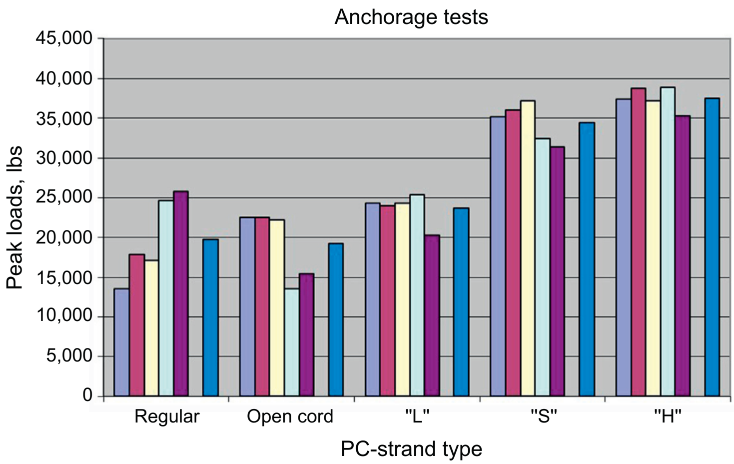

Figure 10.17 Anchorage capacity test results (five samples from each group). The blue columns represent the average peak load value.

an average stiffness of 84.25 tons/in. (295 kN/cm), the stiffness has been improved 2.5 times. This parameter relates directly to the performance that can be expected in underground mines and tunnels in transferring the applied loads from the cable bearing plates back into the rock mass.

10.4.2 Field performance

As everyone knows, laboratory testing can be quite different than the performance that can be expected under field applications. To complete the evaluation of the indented PC-strand, anchorage capacity tests aka pull tests, were completed in an underground coal mine. The immediate mine roof consisted of a typical competent interbedded shale roof. For the tests, standard cable bolt was configured to have 3−0.9 in. (22.8 mm) diameter bulbs located at 6, 18, and 30 in. (15, 46, and 76 cm) from the end of the cable. The 10 ft (3.2 m) long cables were both encapsulated in 4 ft (1.25 m) of resin and pull-tested using a hydraulic ram approximately 60 minutes after installation. The results, shown in Fig. 10.18, indicate that the indented PC-strand actually performed better than the standard cables with respect to anchorage. To help illustrate this performance, the deflection data for the four indented and standard samples were averaged at 10 tons of applied load. The average deflection for the indented samples was 0.209 in. (5.3 mm) and the standard cables was 0.287 in. (7.29 mm). This illustrates that the anchorage along the entire length of the resin grouted cable bolt for the indented PC-strand exceeded the anchorage for a smooth PC-strand with three Garford bulbs applied as a resin anchorage system.

The technology has been expanded and refined to include galvanized strand, without impacting the deformation depth and subsequent anchorage (Fig. 10.19).

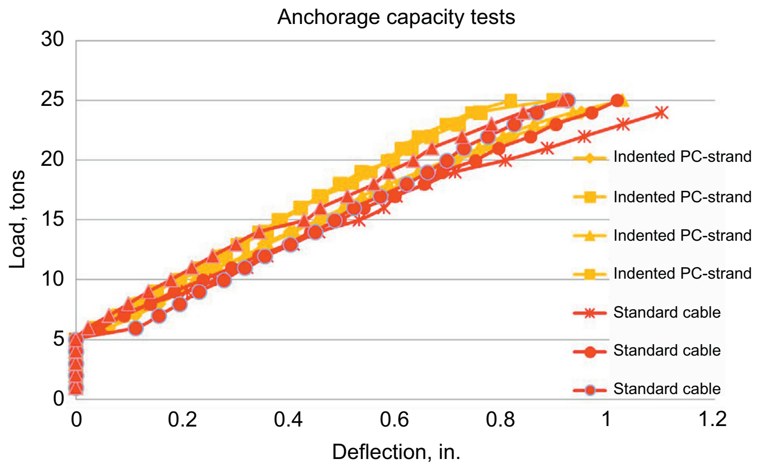

Figure 10.18 The anchorage capacity results for indented PC-strand and standard cables (Garford bulbs).

Figure 10.19 Indented galvanized PC-strand (left) and bright indented PC-strand (right).

Additionally, finite element modeling has been used to optimize the indentation designs (profiles, depths and spacing). The indentations do not impact the strength or ultimate performance of the cable and the technology is spreading rapidly to other cable diameters and configurations (Tadolini et al., 2015).

10.4.3 High capacity cable bolts

A wide variety of post-grouted high capacity cable bolts are currently in use in the Australian coal mining industry, with a few showing up in coal fields around the globe. Each or varying capacity, design, and grouting methodology. The cables include plain-strand, bulbed or nutcaged, smooth and profiled wire packing (different diameter wires within the same cable bolt). At last count there were about 15 different types of groutable cable bolts available, each with different strand designs, capacity, grouting method and hole size (Thomas, 2012). Illustration of the various cable types used in Australian coal mines are shown in Fig. 10.20. Thomas concluded that in comparison to plain strand cables, if the cable is bulbed or nutcaged, the capacity of the anchor can increase by up to 400% of the peak stiffness by one and two orders of magnitude. Although the data was not conclusive, the results also indicate that increasing the hole diameter may have a positive impact on load transfer in the cable of bulbed or nutcaged cables and a negative impact on plain-stand cable. It's important to note that these cable were post-grouted using cementitious cements so polyester resin mixing, where hole diameter and the resulting annulus, were not a critical factor.

A recent development, has been a Hollow-cable that has the king or center-wire removed to permit the pumping of a very fast setting grout. This ensures grouting from top to bottom without the use of grout and breather tubes, can be completed in cycle and post-tensioning can be completed within minutes as opposed to hours or days. The Hollow-cable, shown in Fig. 10.21, includes both smooth and spiral individual wires and has a capacity of 75 tons (670 kN). Encapsulation testing achieves routine stiffness values of 57 tons/in. (200 kN/mm) in a 1.75 in. (45 mm) diameter borehole.

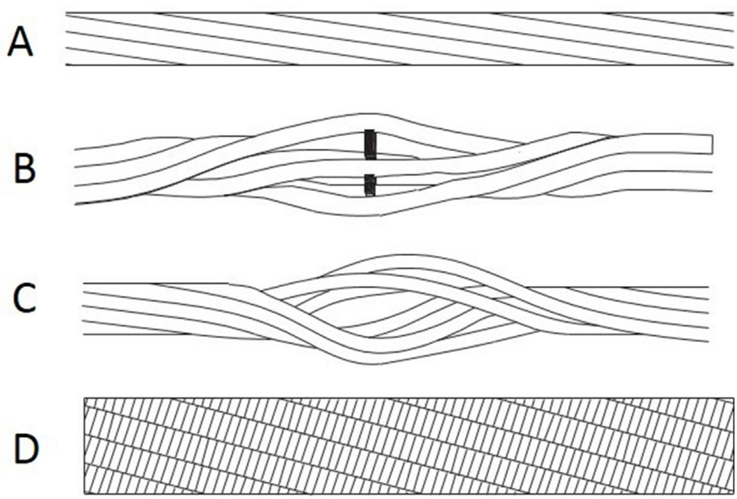

Figure 10.20 Illustration of the various cable types used in Australian coal mines. A, plain-strand; B, nutcaged; C, bulbed; D, spirally indented (Thomas, 2012).

Figure 10.21 Hollow-cable bolt.

10.5 Summary and Conclusions

Without question, resin grouted cable bolts have changed that way that ground control is approached in both mining and civil applications. The speed and capacity of anchorage combined with the flexibility and versatility of these high capacity systems can be found in almost every mining operation. Ways to improve these systems to enhance performance have resulted in several advances in the past few years. Recent innovations in the development of indented PC-strand to enhance anchorage and improve system stiffness have been shown in both laboratory and field applications. No doubt, high-capacity systems that can be anchored and post-tensioned on cycle will continue to gain acceptance and popularity. Anchorage hardware will continue to be improved to optimize cable performance in a wide variety of borehole lengths and diameters.

Initial designs can be simplistic considering suspension weights and mining geometries to determine the required support lengths and spacings. The most common problem is using a spacing that is too large and with not enough cable supports. While cables have high capacities, roof structure, fractures and partings can't be ignored. The best laboratory is underground applications with remedial instrumentation that can be interpreted to modify and improve future designs. Cable flexibility and resistance to shear make them ideal to control high-horizontal movements and resist shear forces. Numerical models have been used to simulate designs and the benefits of high post-tensions, if any, can continue to be investigated and debated.

Acknowledgment

Several outstanding research projects in both the laboratory and field have been completed in the past 30 years to advance the performance and application of cable bolting in mining and civil applications. The largest single innovation, in this author's opinion, was the development of the integrated cable head that permitted the insertion, mixing and developed the capacity of cable bolts. Mr. Doug Gillespie, my mentor, colleague and more importantly, my friend, envisioned and created this unique and paradigm shifting concept.

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