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FACTORS INFLUENCING THE EFFECTIVENESS OF SPLIT SET FRICTION STABILIZER BOLTS*

2.0.0 SUMMARY

Many underground mining operations use Split Set friction stabilizer bolts for rock support. Currently, however, little has been done to quantify the effects of various rock mechanics and operational parameters on the capacity of frictional support systems. The strength of Split Sets is usually measured by means of a pull test wherein a jacking force is applied to the bolt and a slip load is obtained. In order to evolve a rational design procedure for this type of support, an extensive database of over 900 pull test results from more than 50 mines throughout North America has been assembled and analyzed. Associated relevant rock mechanics parameters (rock type and quality) and operational details (drilling method, bit size, drive time, time to pull test) were also obtained, as completely as possible, for each test. Analysis of the information has yielded several charts that relate pull-out strength to relevant parameters and simple statistical analyses were conducted where necessary. Quantified distributions for pull-out strength were also produced for several operating conditions. The factors that most significantly affect bolt strength have been identified and specific applications to design are discussed. The information presented will assist mining engineers in designing safer and more economic support using Split Sets.

* This chapter will appear as a journal article entitled 'Factors Influencing the Effectiveness of Split Set Friction Stabilizer Bolts'.

2.1.0 INTRODUCTION

In the design process for underground excavations, the amount of information concerning rock mass behaviour and rock-support interaction is often of a limited nature. As such, one of the most significant obstacles encountered in rock engineering is the lack of good information. With this problem in mind, a research project was carried out in order to obtain actual test-based information concerning the performance of a particular type of supporting element - the friction bolt.

During the initial phases of this study, it was thought that information could be gathered on both Swellex and Split Sets, the two most common types of friction bolt. Although the effectiveness of both bolt types often is measured by means of a pull test, two major factors restricted the scope of the study to Split Sets: first, the limited availability of Swellex pull test results; and second, a Swellex pull test, more often than not, measures the breaking strength of the steel, rather than the actual frictional performance of the bolt. Splits Sets, on the other hand, almost always fail by slipping at an easily identified and measured load, called the pull-out strength, or slip load.

There is a current trend in rock engineering away from a sole reliance on the traditional deterministic factor of safety approach for stability towards probabilistic analyses which account for the inherent uncertainty associated with many of the design variables. Hoek et al. (1995) give an excellent introduction to the assessment of acceptable risks in design and also to probabilistic stability analyses. In order to perform probability analyses succesfully (see companion paper, Tomory et al., 1997 - Chapter Four), actual data is required to quantify the distribution of the design variables and to calibrate the analysis.

The objective of this study is to identify trends in the field data of Split Set pull-out strengths with regard to rock mechanics and operational parameters. This will be accomplished by means of a graphical approach to the analysis of the data. Relationships between bond strength and key parameters will be identified and plotted. Later work will focus on the statistical aspects of data analysis.

2.2.0 SPLIT SETS AND PULL TESTING

Split Set friction rock stabilizers were developed by Scott (1977) and are manufactured and distributed by the Split Set Division of Ingersoll-Rand. The bolt, consisting of a slotted high-strength steel tube with a face plate, is installed by driving it into a slightly undersized hole. Frictional anchorage, along the entire length of the bolt, is provided by the radial spring force generated by compression of the tube. Splits Sets are used for a wide variety of mining applications throughout many mines worldwide.

The pull test is the method which is commonly used for determining the effectiveness of Split Set friction stabilizers. Bolts are tested at any time after installation by applying a load to the pull collar and increasing it until the bolt slips. A typical load-deformation curve for a pull test is shown in Fig. 2-1.

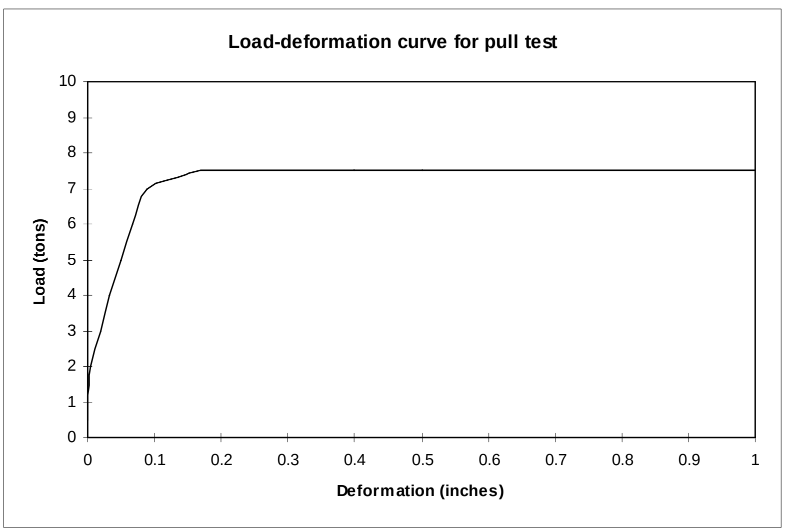

Figure 2-1. Typical load-deformation curve for a pull test on a Split Set friction stabilizer.

The first part of the curve represents the elastic deformation of the steel and the seating of the test apparatus and the bolt. The initial slip load, which is the load at which the bolt firsts moves in its hole, is considered to be the bolt’s pull-out strength (in the case of the example shown, the pull-out strength is 7.5 tons). Once slippage has begun, the load remains constant as shown.

The magnitude of the slip load depends on many factors, including the contact area between the Split Set and the rock, the size of the drill hole into which the bolt is installed, the characteristics, properties and type of the rock, the time elapsed between bolt installation and pull test, the quality of installation and other less significant factors. Some of these, such as rock type, drilling bit size and time to test are easily obtained. Others, such as contact area and installation quality are either very difficult to determine or are not readily quantifiable.

The pull test should not necessarily be viewed as a definitive measure of a bolt's capacity but rather as an index test, one that can give a reasonably good idea of the bolt's expected performance. An analysis of the effectiveness of Split Sets bolts can only be successful if the many factors which influence bolt behaviour are considered along with an interpretation of pull test results.

2.2.1 Description of Study

As part of the background research for this paper and others, an extensive database of over 900 pull test results was compiled from about 50 mines throughout North America, representing a very wide range of ground conditions and applications. An effort was made to obtain detailed information, for each individual test, about the general conditions and about several parameters which influence bolt effectiveness. If possible, information was gathered on the following: bolt type (i.e. SS33, SS39 or SS46; see Table 2-1), bolt length, drilling bit size, drive time, driver equipment, time elapsed from installation to test, rock type, rock quality (RMR), specific bolt application and pull-out, or slip load. Some of this information will be discussed subsequently in greater detail. The full data list is given in Appendix C.

Split Set Specifications

Split Set model	SS33		SS39		SS46	
Nominal outer diameter	33mm	1.3 in.	39mm	1.5 in.	46mm	1.8 in.
Bolt lengths	0.9 to 2.4 m	3 to 8 ft.	0.9 to 3.0 m	3 to 10 ft.	0.9 to 3.6 m	3 to 12 ft.
Capacity of steel, average	10.9 tonnes	12 tons	12.7 tonnes	14 tons	16.3 tonnes	18 tons
Capacity of steel, minimum	7.3 tonnes	8 tons	9.1 tonnes	10 tons	13.6 tonnes	15 tons

Table 2-1. Split Set specifications. After Split Set Division, Ingersoll-Rand Company.

The simplest way to express the pull-out strength in a way which is common to all test results is to divide the pull-out load (normally measured in tons) by the length of the bolt (measured in feet) to obtain a value in tons/foot. This measure is reasonable because it can be assumed that bond strength is developed along the entire length of the bolt. Fig. 2-2 shows a histogram and an initial statistical analysis of the pull-out strength values (in tons/ft) for all test results collected in this study. Imperial measurements are used in this study because the vast majority of mines use them and almost all mines measure pull-out strengths in tons and bolt lengths in feet. Metric conversions are provided in Appendix A.

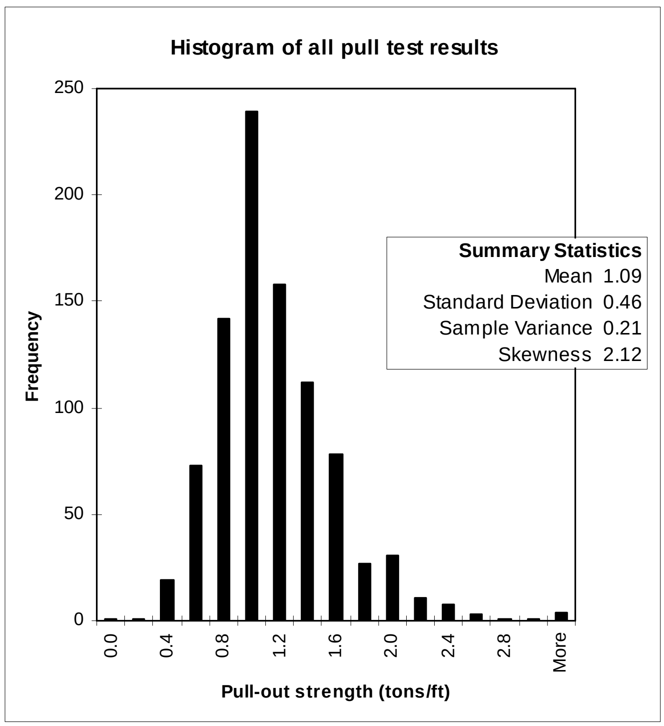

Figure 2-2. Histogram showing the distribution of pull-out strengths for all data collected in study.

As can be seen, the histogram closely resembles a normally distributed random variable with some degree of skewness. The mean pull-out strength is 1.09 tons/ft with a standard deviation of 0.46. It is beyond the scope of this paper to discuss the characterization of this distribution and the more involved statistical aspects of the sample set and its subsets; these will be considered in a later paper.

The histogram shown in Fig. 2-2 should not be considered as the definitive distribution for Split Set pull-out strengths in specific probabilistic stability analyses because it includes all test results representing a very wide range of conditions. The test results can be broken down into more specific design applications, based on, for instance, rock type and/or drill bit size, so that more accurate and representative distributions can be determined.

2.3.0 FACTORS ASSOCIATED WITH ROCK TYPE

2.3.1 Rock Classification

Given the very limited nature of the information available concerning rock type and quality at many of the sites where the pull tests were conducted, it was impossible to apply any of the more involved rock mass classification or strength charac-terization systems to all the data. Many of these require fairly good knowledge of the condition and nature of the joints, groundwater conditions and of the strength of the rock mass (i.e. Hoek-Brown, GSI, RMR, Q, etc…). For many of the test results collected in this study, such information was simply not available. The information from the various mine sites varied in detail; some of the mines kept fairly good records of rock type and quality while others simply noted the rock types and perhaps a brief qualitative description. For instance, RQD or RMR was available for some but not all of the rock types encountered in the study. In any case, given a certain number (about 300) of test results where the RMR of the rock was known, there was no observable relationship between RMR and pull-out strength (see Fig. 2-3).

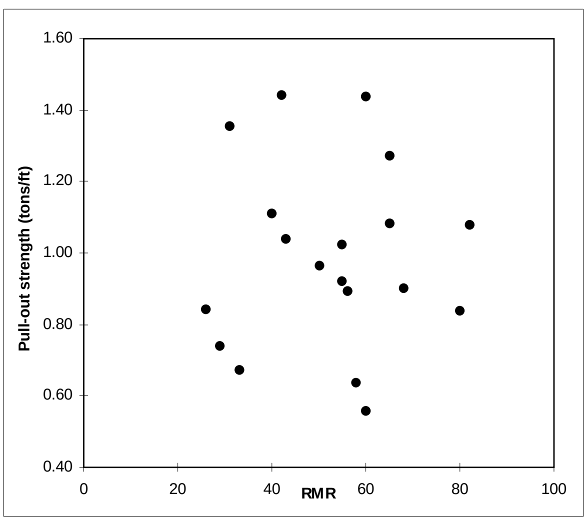

Figure 2-3. Relationship between Rock Mass Rating and pull-out strength. Each point in the plot represents approximately 10 pull tests; i.e. often several tests were conducted in one location where a single value for RMR was recorded.

To account for the possibility that there may be underlying trends in this plot caused other factors, the data was analyzed in terms of bit size, rock type and time to test. There were no observable trends which could clarify the plot.

For the purposes of classifying the rock types encountered in this study, the classification system of Terzaghi (1946), with some modifications, was found to be the most appropriate. Rock types can be divided into four very broad categories based on easily identifiable physical characteristics which dominate rock mass behaviour. These categories are summarized below:

Laminated rocks. This category includes crystalline or metasedimentary rocks which are strongly laminated or foliated; including schists, laminated argillites, shales and other hard laminated rocks. The individual laminations usually have moderate to little or no resistance against separations along the boundaries between them and surface spalling is common. The laminations may or may not be weakened by transverse jointing. The values for RMR are typically around 50, ranging from about 25 to 65.

Competent rocks. These include intact and weakly to moderately jointed crystalline and hard sedimentary rocks; including granite, gabbro, rhyolite, quartzite, hard sandstones, dolomite, hard limestones and others. The blocks between joints are locally grown together or so intimately interlocked that vertical walls do not require lateral support. In rocks of this type, bursting and spalling may be encountered. The RMR values are above 50, typically ranging from 60 to 80.

Altered, weathered or broken rocks. These include weathered crystalline rocks, rock in shear zones, certain ores, cemented gravels and others. The structure of these rocks is blocky, seamy or crushed, consisting of generally intact fragments which are entirely separated from each other and imperfectly interlocked. In such rocks, vertical walls require lateral support. Rock mass deformations are usually by block movement. The values for RMR are below 50.

<u>Soft rocks</u>. These include extremely weathered rocks, weakly-cemented clays, talc, evaporites and others. This category includes those rocks which Terzaghi describes as squeezing and swelling. Squeezing rock slowly advances into the excavation without perceptible volume increase (stress driven) while swelling rocks move into the excavation chiefly on the account of expansion (chemical process). Rock mass deformations are generally plastic. For the purposes of this study, permafrost-affected rocks were included in this category. The values for RMR range from 20 to 60.

2.3.2 Variation in Pull-out Strength with Rock Type

For the four different rock types described above, a significant amount of variation in the distribution of pull-out strengths was observed. Normalized histograms showing the occurrence of values for pull-out strength, as a percentage of the total number of pull tests in each rock type category, are shown in Fig. 2-4.

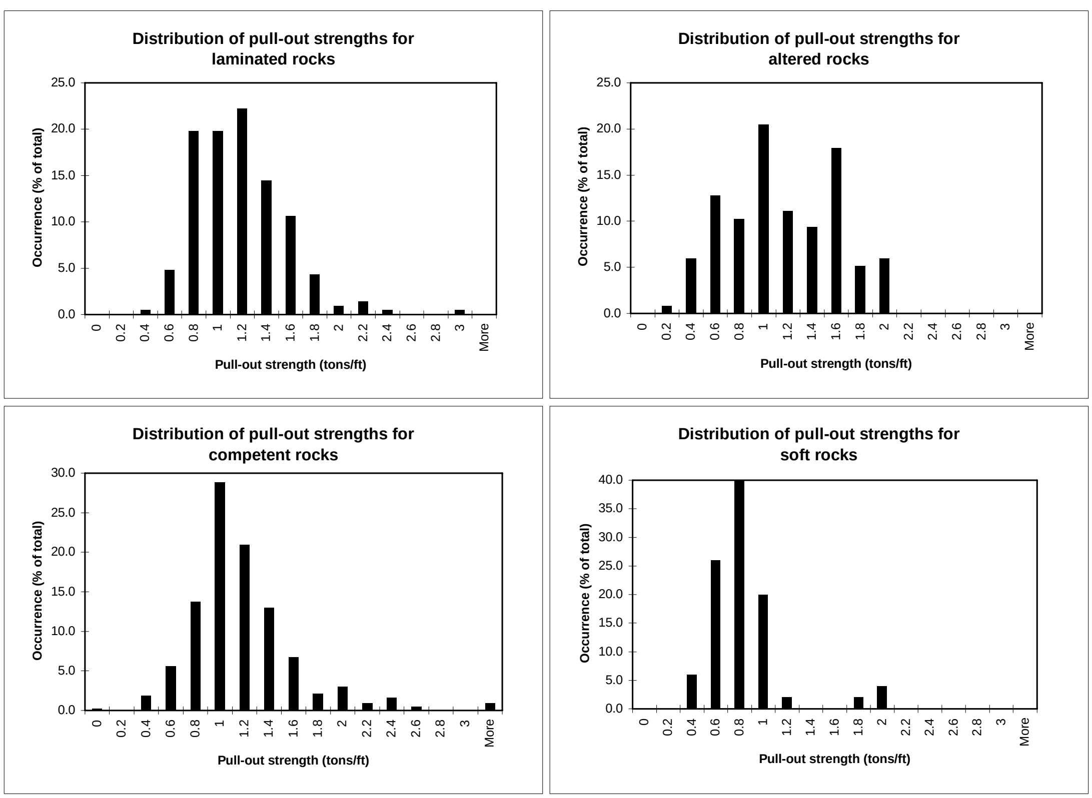

Figure 2-4. Normalized histograms showing the distribution of pull-out strengths for the four different rock types, all test results.

Note that the distributions for competent and soft rocks are grouped more tightly than the ones for laminated and altered rocks. Additionally, the former two could be more easily characterized as normally distributed random variables. The mean pull-out strength for competent rocks is 1.12 tons/ft, with a standard deviation of 0.46, while the mean for soft rocks is 0.75 tons/ft, with a standard deviation of 0.38.

For altered rocks, there appears to be a wide range of values for pull-out strength with two distinct peaks, one at 1.0 and one at 1.6 tons/ft. Upon close examination of the test results, there is no readily apparent reason for this. Both peak groupings include rocks of similar type, in similar conditions and installed in similar-sized holes. Bond strength development with time is also not the cause of the second peak because the great majority of the results (for altered rocks) were of pull tests conducted immediately after bolt installation. A possible explanation for the second peak is that many of the test results in that group were for bolts installed in highly stressed (and fractured) ore zones where the hole was drilled with an undersize bit.

In the case of laminated rocks, pull-out strengths of 0.8 to 1.4 tons/ft are common. However, this broad range of values can be attributed to the marked development of bond strength with time exhibited by bolts installed in laminated rocks (many of the tests were conducted days or weeks after bolt installation). Thus, the distribution for pull-out strengths in laminated rocks (as shown in Fig. 2-4) is not as wide as it may appear initially. The issue of bond strength increase over time is discussed in a later section.

2.4.0 FACTORS ASSOCIATED WITH INSTALLATION

2.4.1 Installation Quality

The installation of Split Set stabilizers is a fairly straight-forward procedure and can be performed easily by trained personnel. The diameter of the bit should be measured and the length of the hole should be at least two inches longer than the bolt. Since Split Sets are driven through a pounding action, it is essential that the end edge of the bolt be flared over the ring by the driver tool to achieve proper contact of the ring to the roof plate. The bolts should not be overdriven but placed tightly against the rock so that a slight deformation in the roof plate is visible.

Other installation factors affecting bolt capacity are hole roughness and curvature. Crooked or rough holes do not adversely affect the performance of a Split Set, but rather they increase the anchorage and hence the pull-out strength .

2.4.2 Drive Time

A practical method for determining the quality of an installation without a pull test is to measure the length of time required to fully drive the bolt against the rock; in other words, the drive time. The drive time is dependent on the friction that must be overcome by the driving tool to insert the bolt fully. A longer drive time is indicative of greater friction between the rock and the bolt surface and conversely a shorter drive time indicates less friction. As a result, there is a direct relationship between drive time and immediate capacity (rock movements over time may give bolts with otherwise low drive times higher bond strengths).

Bolts that require a greater amount of work energy to install, as manifested by higher drive times, will have a higher pull-out strength when tested. As such, for each particular driver type, because the work energy delivered by different drivers is different, there should be a relationship between drive time and pull-out strength. In fact, such relationships were observed for several driver types in the collected data. For example, Fig. 2-5 shows the relationship between drive time and immediate pull-out strength for the commonly used Jackleg driver.

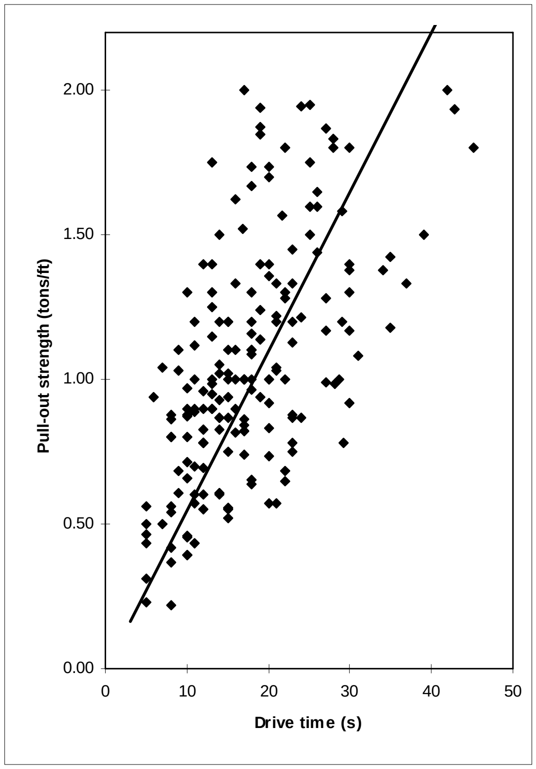

Figure 2-5. Relationship between drive time and pull-out strength for a Jackleg driver with SS39 bolts. The line has been fitted using linear regression techniques.

The scatter of the data points can be, to some extent, attributed to such factors as differing bit size or rock type, as shown in Fig. 2-6 for the latter; there was insufficient data to observe properly the effect of bit size on drive time. In general, however, the scatter is what could be anticipated from a data set composed of information from a very wide range of sources. The relationships appears to be linear. A trend line was produced for each using linear regression in order to show a mean relationship between drive time and pull-out strength.

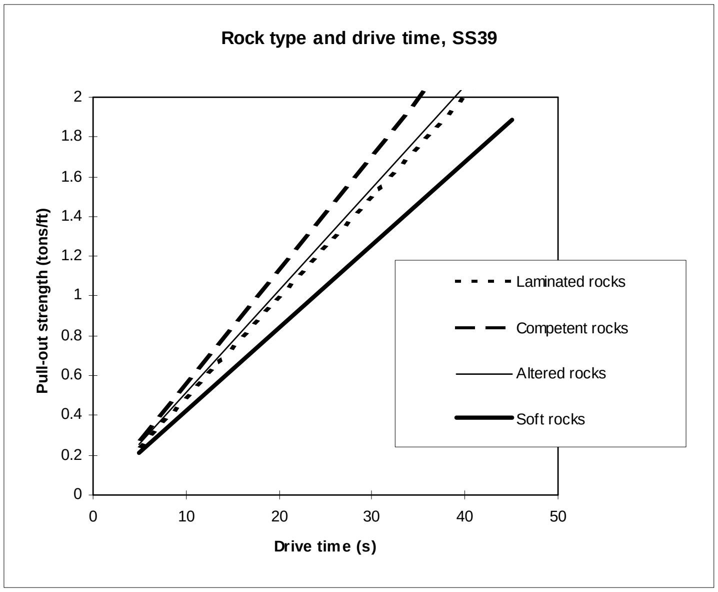

Figure 2-6. Relationship between drive time, pull-out strength and rock type for a Jackleg driver with SS39 bolts. The lines have been fitted using linear regression.

One further, though unquantifiable, reason for the scatter of the points in Fig. 2-5 is that the pneumatic line pressure is not necessarily a fixed quantity. At sites where the tool is further from the main compressor unit, there will naturally be a lower pressure available for bolt driving. If the operating pressure was known at the bolt installation sites, which was not the case for the tests in this study, then a somewhat more accurate relationship between drive time and pull-out strength could be obtained.

The drive time can be a very practical and easy indication of installation quality. Once the characteristic drive time vs. pull-out strength plot for a driver type is known (such as the ones shown in Figs. 2-5 and 2-6), then a simple measurement of the drive time can give a good day-to-day measure of installation quality.

2.4.3 Slot Closure

Split Sets are one of the only support fixtures where a miner can visually observe the quality of installation. By shining a light down the length of the tube, a miner can observe the degree of slot closure along the bolt's length. A very rough estimate of capacity can be made; the narrower the slot, the higher the anchorage. Scott (1996) reports that if the slot is closed 1/16 of an inch, then there is full rock-metal contact around the Split Set. If the slot is the same size as before installation, then the hole is larger than the Split Set and there is zero or near-zero anchorage.

With slot closure, the Split Set bolt is deformed beyond the yield point and into the cold working portion of a stress-strain curve. Anchorage, or bond strength, is produced by the reaction of the spring-like Split Set against the walls of the drill hole. If the bolt is removed, and the steel unloaded, there will be some amount of spring-back, typically around 1/32 of an inch on the diameter of an SS39 bolt.

2.4.4 Bit Size

To achieve proper slot closure and to develop bolt anchorage, the hole should be drilled with a bit of a diameter slightly less than that of the Split Set (i.e. 1.3 in. for SS33 and 1.5 in. for SS39). Since the bolts are deformed plastically upon insertion in the hole, the bit size is not overly critical. If Split Sets were designed to be loaded only in the elastic range of the steel, then the hole size would be supercritical and it would prove impractical, if not impossible, to drill holes within appropriate tolerances.

Given that the hole size should be slightly smaller than the diameter of the bolt, there will still be variations in bond strength with different bit sizes for different rock types. The diameter of the drill hole will not always be the same as the diameter of the drill bit used to do the drilling. For instance, there will be a significant degree of overbreak in holes drilled in soft or broken rocks while holes drilled in more competent rocks will have a diameter closer to the actual bit size. As a result, bond strength will vary for the same drilling bit size in different rock types. For example, if the hole for an SS39 bolt (diameter of 1.5 in.) in weathered or broken rock is drilled with a 1.438 in. bit, the developed bond strength will be lower, because of greater overbreak in the hole, than the strength developed in a same size hole in stronger rock.

The variation in pull-out strength with bit size for all SS39 bolt test results, regardless of rock type, is shown in Fig. 2-7. As can be seen, there is a trend of decreasing pull-out strength with increasing bit size. To further analyze the relationships between bit size and pull-out strength, the type and quality of the rock in which the hole was drilled must be considered.

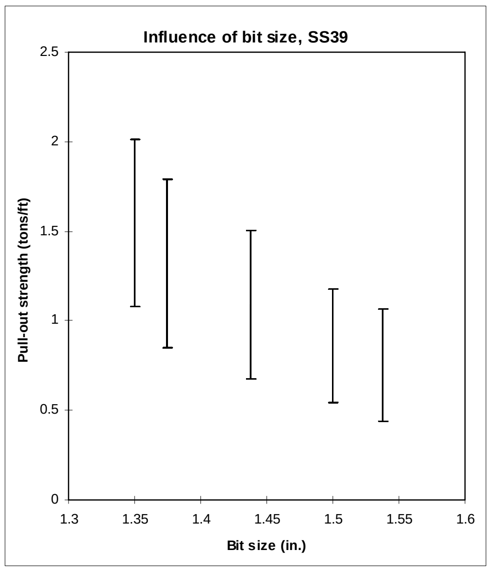

Figure 2-7. Relationship between bit size and pull-out strength for all SS39 test results (numbering over 450). The results are plotted in error bar form for the five most common bit sizes (1.35, 1.375, 1.438, 1.5 and 1.538 in. sizes). Each bar represents the distribution of test results for its particular bit size. The bars are centred on the mean, with each extremity positioned one standard deviation on either side of the mean.

The relationship between bit size and pull-out strength for the four different rock types is shown in Fig. 2-8. By plotting the data in this form, a clarification of the error bar plot in Fig. 2-7 is obtained.

As can be seen, competent rocks are the most sensitive to the size of the drilling bit. This is attributable to the general nature of the rock; it is not easily deformed or broken. Due to minimal overbreak, the actual hole diameter in such rocks is close to that of the drilling bit and, as such, a fairly clear relationship between anchorage and bit size can be observed.

Additionally, rock movements by squeezing, breaking or shearing that could increase bolt bond strength are not significant.

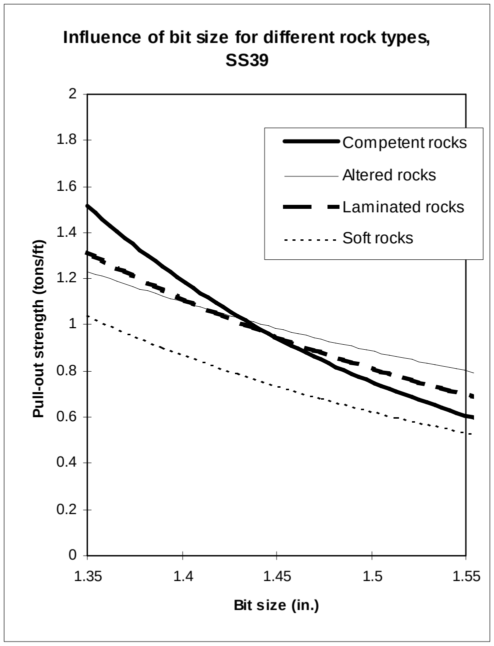

Figure 2-8. Relationship between bit size and pull-out strength for all SS39 test results for the four different rock types. The trend lines shown were fit to the data using second order regression.

For laminated rocks the influence of bit size on pull-out strength is not as pronounced. For these, breakage and movement of the rock mass during and immediately after hole drilling and bolt insertion combine to lessen the influence of bit size on bond strength. In particular, shear movements along lamination or foliation planes cause a general increase in bolt anchorage by introducing a confining stress.

The pull-out strength, in the case of altered, weathered or broken rocks and soft rocks, appears to be influenced by bit size to an intermediate degree. For these rock types, overbreak during drilling is a greater concern. However, the effects of overbreak are mitigated, to varying degrees, by deformations of the mass during and after drilling and installation. These deformations, whether plastic or along fractures can cause closure of the rock mass around the bolt, increasing confinement.

2.5.0 STRENGTH DEVELOPMENT

2.5.1 Load Reaction Curves

The response of a support system to excavation boundary displacement can be described by a load reaction curve, as shown in Fig. 2-9.

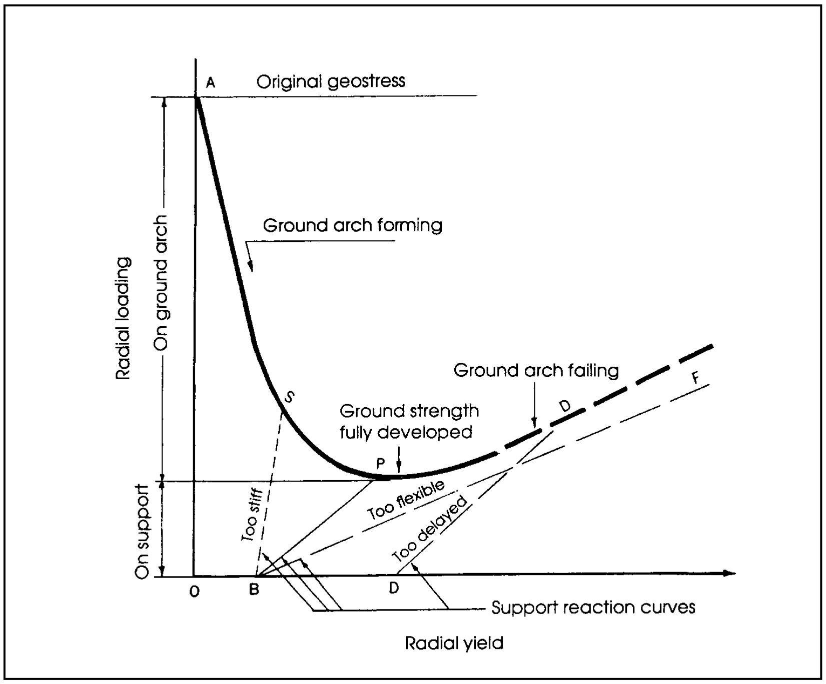

Figure 2-9. Load reaction curve showing the response of a support system to excavation boundary displacement. From Scott, 1989 (reprint of ground reaction curve developed by Deere and Peck).

During mining, a certain amount of deformation occurs ahead of the advancing face of the tunnel. According to Hoek et al. (1995), at the face itself, approximately on third of the total radial deformation has already occurred and this deformation cannot be recovered. In addition, there is always a stage in the excavation cycle in which there is a gap between the face and the closest installed support element. Hence, further deformation occurs before the support becomes effective. The total initial displacement, or rock mass relaxation, corresponds to section OB on the horizontal axis in Fig. 2-9.

Short of employing massive and expensive pre-loaded supports, there is little that can be done to prevent this initial load relaxation and rock movement. As such, it is important to install support which possess adequate stiffness to allow ground strength to become fully developed as shown in the figure. In some conditions where excessive movements are expected, Split Sets can be an effective mode of support because of their deformation characteristics.

2.5.2 Split Set Deformation

When installed, a Split Set bolt has a certain anchorage or bond strength. When a load is applied, the initial deformation, up to the total bond strength developed, will be that of the steel yielding in the elastic range and of the test apparatus seating itself. As the load on it reaches or exceeds the total available bond strength, the bolts will slip a small amount and again be capable or supporting a load equal to the available bond strength. This process can continue indefinitely, with the bolts alternately sticking and slipping at a more or less constant load. The results of a load-deformation test carried out on an SS39 installed in hard shale by Scott (1977) are presented in Fig. 2-10. They demonstrate that there is no loss of bond strength with bolt slippage in the hole.

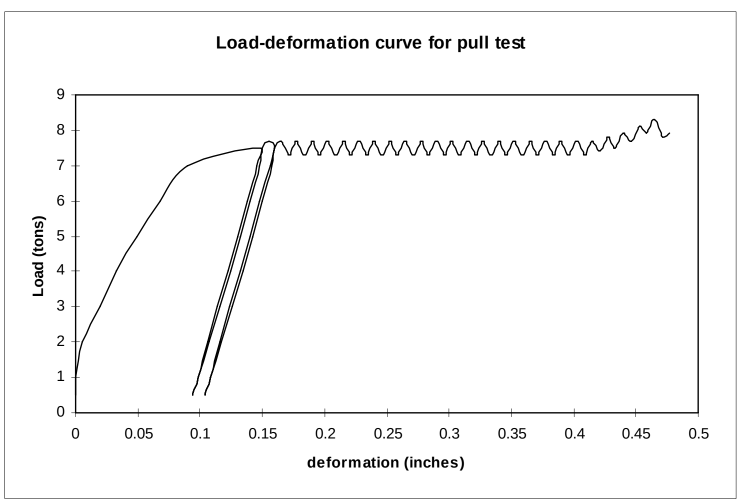

Figure 2-10. Load-deformation curve for a pull test carried out on a 5 ft. SS39 immediately after installation. The bolt was loaded until initial slippage, unloaded and reloaded twice and then

pulled out of the hole for a a full 0.5 inches. Note that an approximately constant load of 7.5 tons was reached. From Scott, 1977.

The ability of Split Sets to stick and slip (referred to as stick/slip behaviour) is considered to be their chief advantage. This allows the bolts to adapt to extensive ground movements while maintaining a certain constant load level; other types of bolts under identical conditions would rupture because of their higher stiffness. Fig. 2-11 shows a comparison of load-deformation curves for various support elements including Split Sets.

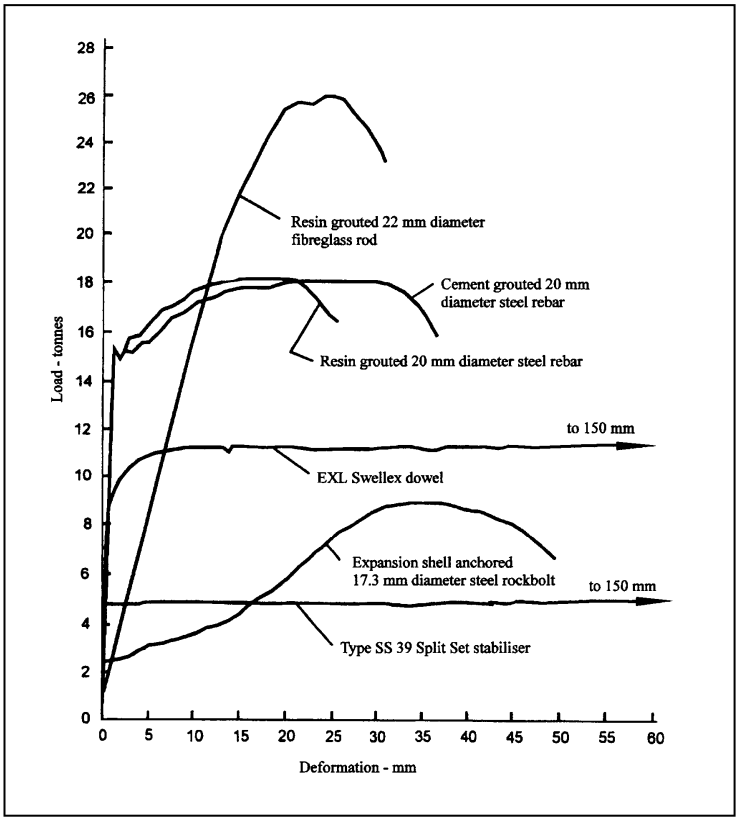

Figure 2-11. Load-deformation curves obtained in tests carried on various support elements. High strength reinforced concrete with a uniaxial compressive strength of 60 Mpa was used for the test blocks and holes were drilled with a percussion rig to simulate in-situ rock conditions. From Stillborg, 1994

2.5.3 Load Development with Time

As deformations occur over time in the rock mass surrounding an excavation, there is an increase in the confining stress on supporting elements. Split Sets not only demonstrate stick/slip behaviour as discussed, but they also yield and adjust to the load reaction curve with constantly increasing levels of restraint. In other words, greater anchorage, or bond strength, is developed between the rock and the bolt with time. As the system reaches equilibrium, and the ground strength becomes fully developed, the load in the supporting elements reaches a maximum.

This is confirmed by pull tests carried out on SS33 bolts days, weeks and months after installation that show higher than average values for pull-out strength. Load development varies with rock type, as shown in Figs. 2-12 and 2-13, which plot pull-out strength against time for laminated and competent rocks respectively. Note that these results represent the mean of all tests, so they incorporate all results, regardless of bit size. The plots could be further broken down into a series of curves representing different bit sizes.

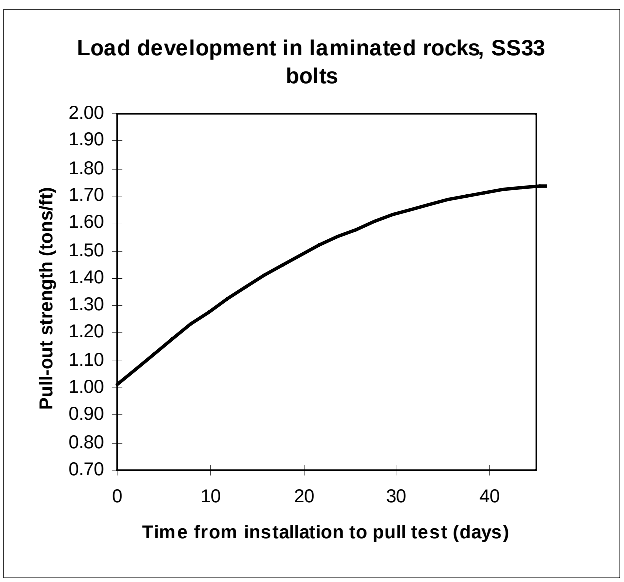

Figure 2-12. Load development with time for SS33 bolts installed in laminated rocks. The curve was fit using second order regression.

There was not enough data available in this study for observing load development with time in soft or altered rocks. There was also insufficient data to consider load development in SS39 bolts but presumably the general trends would be identical.

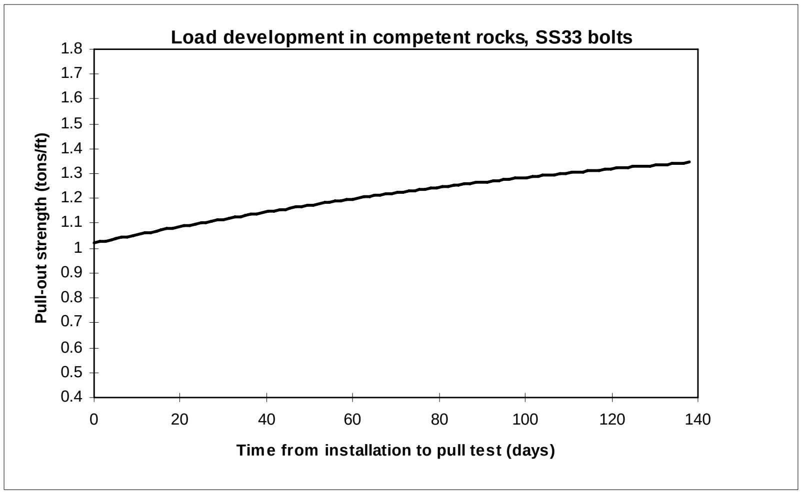

Figure 2-13. Load development with time for SS33 bolts installed in competent rocks. The curve was fit with second order regression.

These figures can be compared with earlier results published by Scott (1980) and shown in Fig. 2-14. It should be noted that Figs. 2-12 and 2-13 illustrate load development in SS33 bolts while Fig. 2-14 shows the same for SS39 bolts. In all cases (in Figs. 2-12, 2-13 and 2-14), the pull-out strength increases with time. The rate of increase depends on the rock type.

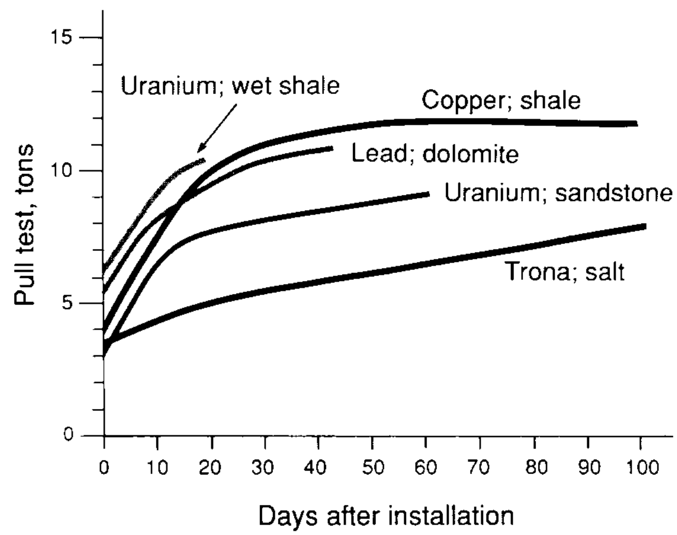

Figure 2-14. Load development with time for several different rock types. The pull-out load is given in tons for 5 ft. long SS39 bolts. From Scott (1980).

For example, in laminated rocks, stress redistribution and rock mass movement after mining tend to cause shearing along lamination surfaces. These movements produce slight offsets in the Split Sets which increase the anchorage or bond strength. In such conditions, the amount of stick/slip behaviour is diminished and a greater degree of lock-up occurs due to shearing.

Note that in Fig. 2-13, for laminated rocks, there is a 70% increase in load over a 45 day period. The load appears to level off to a maximum after about 40 days. A similar rate of load development can be observed in Fig. 2-14 for the case of the copper mine shale, a laminated rock.

Where Split Sets are installed in competent rocks, the rate of load development is not as pronounced and it appears to be more uniform. In such rocks, load development is caused by mass deformations which tighten the rock mass around the bolt rather than by shearing.

A comparison of the distributions obtained in tests performed immediately after installation and in tests performed seven to twenty one days after installation in laminated rocks is shown in Fig. 2-15. Note that since the distributions are normalized histograms, an aggregate distribution would not be the same as the distribution shown in Fig. 2-4 for laminated rocks.

Also note that the mean value for pull-out strength is 30% higher for the tests conducted one to three weeks after installation. Essentially, the distribution curve for pull-out strengths moves to the right with time. The broad range of values obtained for pull-out strengths for laminated rocks, as shown in Fig. 2-4, can thus be attributed to the development of load with time in Split Sets. Fig. 2-16 shows a similar pair of distributions for competent rocks. As with the load development curves, these histograms include test results including all bit sizes. The result is an inherent spread of the results.

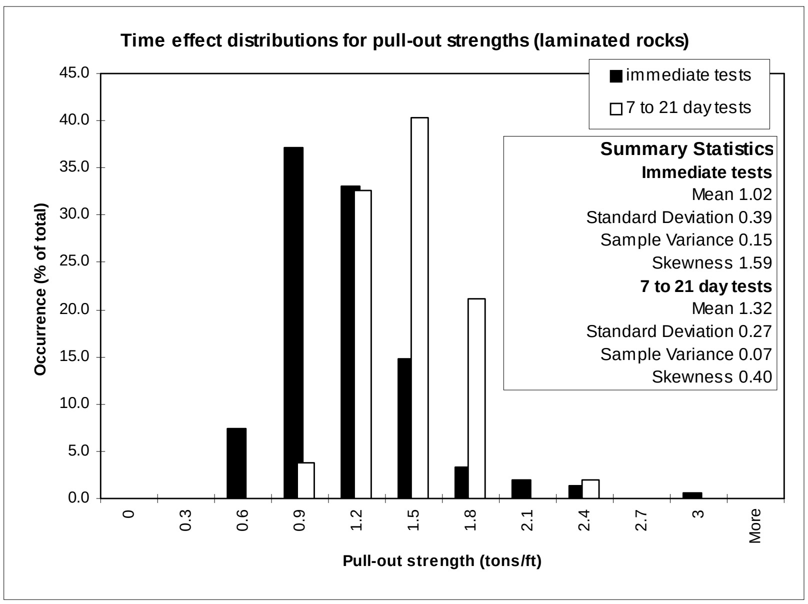

Figure 2-15. Normalized histograms showing the distribution of pull-out strengths for tests performed immediately and between a week and three weeks on SS33 Split Sets installed in laminated rocks.

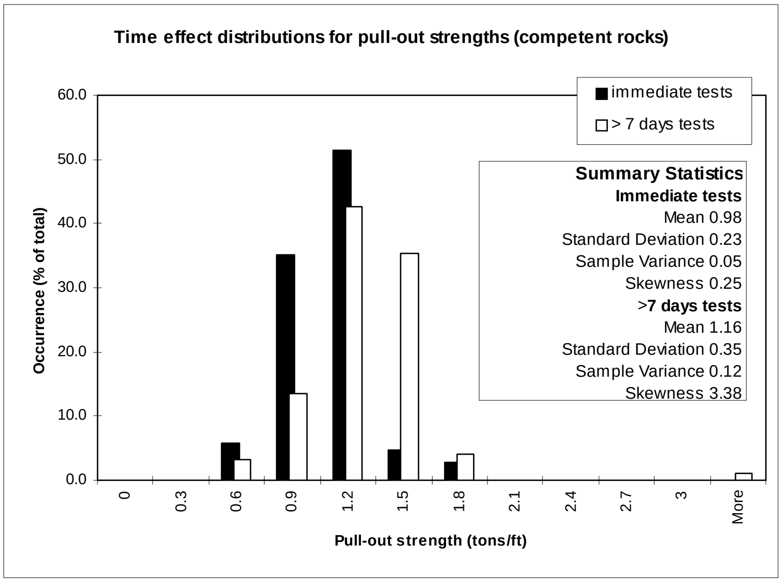

Figure 2-16. Normalized histograms showing the distribution of pull-out strengths for tests performed immediately and after more than a week on SS33 Split Sets installed in competent rocks.

2.5.4 Steel Failure

As shown, a significant amount of load development will occur in Split Sets installed in laminated rocks. In addition, Scott (1996) indicates that similar behaviour can be expected in highly stressed ground. In these cases, movements along cracks or shearing planes which intersect the length of the bolt produce offsets which may lead to the bolt locking up.

Excessive lock-up or load development is not necessarily desirable since one of the reasons for Split Set use is that they yield with the rock mass in a controlled manner. If the loads reach high enough values then failure of the steel will occur. This should not be allowed to happen because it could result in an uncontrolled failure of the excavation. For Split Sets to maintain their yielding behaviour, the load developed over time should remain less than the failure load of the steel; which is, on average, 12 tons for SS33 bolts and 14 tons for SS39 bolts or as a minimum, 8 tons for the SS33 and 10 tons for the SS39.

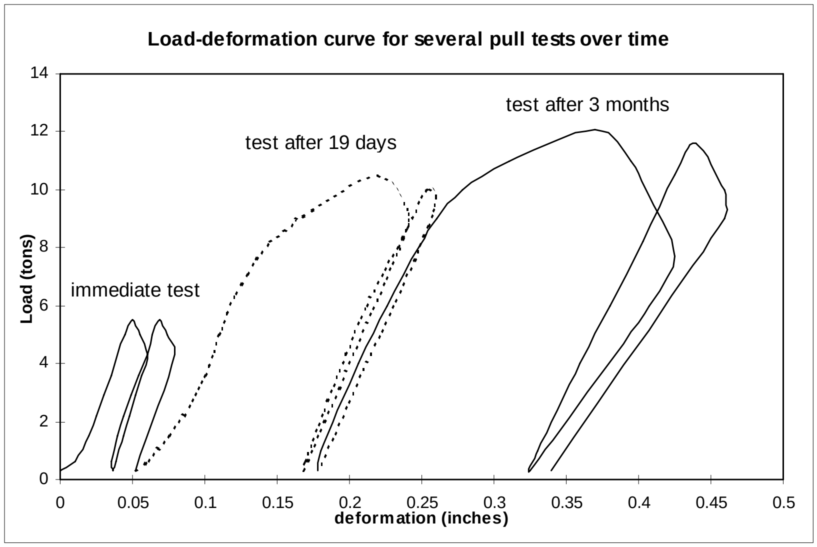

Figure 2-17. Load-deformation curves for three pull test carried out on the same 5 ft. SS39 bolt in hard shale: at the time of installation, at 19 days and at 3 months. From Scott, 1977.

Fig. 2-17 shows the load-deformation curves for three separate pull tests conducted on the same SS39 bolt: at the time of installation, at 19 days and at 3 months. Each test shows a progressive increase in anchorage with time; from 5.25 tons, to 10.25 tons and then to 12 tons. Again, these tests were conducted on bolts installed in a hard shale in an area showing significant rock deformation caused by stress. After three months, a load greater than the minimum steel breaking load has been developed in the Split Set. This is still acceptable, but further load development will cause the steel of the bolt to break, potentially causing an uncontrolled failure of the support element and possibly also the excavation if progressive overloading of bolts in the pattern occurs.

In the case of SS39 bolts, an ultimate tensile strength of 14 tons is available. If the bolt is installed in a highly stressed rock, or in a laminated rock, where large deformations are expected, it will be necessary to install the bolt at a low initial anchorage of as low as, say, 2 tons for a 5 ft. bolt. In this way, 12 tons of effective support capacity are available in the Split Set during the period of rock mass relaxation on the load reaction curve. Thus, when the ground strength becomes fully developed and the support is fully effective, there will be a load in the Split Set near to but not exceeding the steel failure load. If the Split Set were installed with an initial anchorage of 6 or 7 tons, then the strength available for load development is less and bolt overloads may occur. As a result, it is very important to be able to predict, with a fair degree of accuracy, the loads which can be anticipated under certain conditions.

In laminated rocks, where the observed load development reaches 1.7 tons/ft, bolt lengths should be limited to 5 ft. for the SS33 and 6 ft. for the SS39 if installed under normal drilling conditions. This length limit, however, could be increased if the bolts are installed in larger diameter holes where the initial anchorage is lower.

2.5.5 Bolt Length

The effect of bolt length on pull-out strength was also considered. Although it has been suggested that longer-length bolts (longer than 6 ft.) are more prone to lock-up than shorter ones, the same was not found in this study. As shown in Fig. 2-18, for SS39 bolts, there may even be a decrease in the bond strength with increasing bolt length. Nevertheless, there are two test results for 8 ft. bolts which show very high pull-out strength values; these may indicate bolt lock-up.

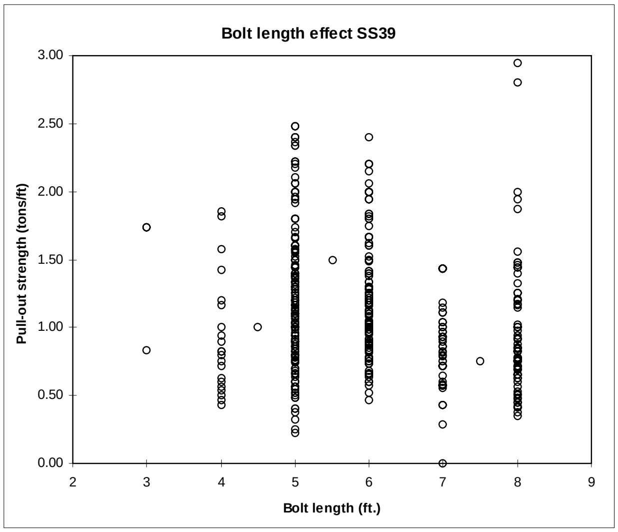

Figure 2-18. Relationship between bolt length and pull-out strength for SS39 bolts.

To account for the possibility that there may be underlying trends in Fig. 2-18 caused by different factors (as was the case for the bit size vs. pull-out strength relationship), the data was analyzed by separating, in turn, the points into the bit size, rock type and time to test groups used earlier. There were no observable trends which could clarify the plot.

2.6.0 RECOMMENDATIONS FOR DESIGN

2.6.1 Range of Application

Before making any specific comments concerning the anticipated strength of Split Sets, some general considerations must be addressed and the range of applicability of Split Sets must be defined.

Split Sets should never be expected to carry large loads. On the contrary, they are designed to yield in a controlled fashion under comparatively limited loads. This is their chief advantage. However, the limited load-carrying capacity of Split Sets does preclude their exclusive use in some applications (high-modulus rock, for instance). Nevertheless, in these situations, they can be employed in conjunction with stiffer elements, such as resin-grouted rebar, to provide an effective means of supporting an excavation. Additionally, in conditions where the primary mechanism of excavation support is suspension of the rock mass, Split Sets are not an effective means of support. In these cases, cables, resin-grouted rebar and point-anchor bolts are more suited to the task.

Split Sets are particularly good for supporting rock where high stress and strain levels are encountered. Stress relaxation and movement of the rock mass around the excavation, and in particular if the rock is brittle, produce offsets in the Split Sets, increasing their anchorage. If these conditions are expected then Split Sets should be installed at a low initial anchorage to allow it to reach maximum deformation without steel failure. As discussed earlier, the same holds true for Split Sets installed in laminated rocks.

In hard, brittle rocks where surface spalling is a problem, Split Sets can be a very effective means of retaining the broken pieces of rock in place. Although this condition does not represent a major stability concern, broken pieces should be kept in place to prevent progressive spalling and unravelling. In these situations, Split Sets are best installed with wire mesh. Note that although Split Sets and mesh control spalling, they cannot prevent its initiation.

In rockburst situations, Split Sets have the advantage of yielding under constant load, which enables them to restrain broken rock which would otherwise be ejected from the face. In these situations, where other, stiffer, support elements may fail, Split Sets can move up to several feet in their hole without failing. In such events, Split Sets act as dynamic dampers, transferring the burst energy to pull-out force. Split Sets are used widely in burst-prone ground in both the United States and South Africa. However, progressive bursting may be a problem for Split Sets because, after each successive burst, a certain degree of lock-up occurs. The bolts would then be locked in so tightly that either steel failure occurs or the plate is ripped off the head of the bolt. In these situations, an alternating pattern of Split Sets and resin-grouted rebars has been found to be effective.

A major concern associated with Split Sets is their useful life span. They are susceptible to corrosion and in some severely corrosive groundwater conditions, they can become ineffective after a period of seven or eight months or even as little as two months. In less corrosive environments, life spans of two to six years are common. Galvanized and stainless steel Split Sets are available for use in permanent excavations. Split Sets are well suited to temporary support applications, such as shaft sinking, where support is required only for a few days until the advance of the permanent concrete liner.

2.6.2 Determining Bond Strength

For the purposes of design and analysis (conventional or probabilistic), several recommendations can be made with regard to the bond strength which Split Sets could be expected to develop in specific rock types and for specific drilling bit sizes.

Firstly, it should be noted that the strength developed in SS33 and SS39 bolts appears to be very similar (measured in tons/ft), as shown in Fig. 2-19. In general, the distribution for the

SS39 appears to be somewhat more spread out than the distribution for the SS33. For instance, there appears to be a slightly greater proportion of test results yielding higher pull-out strengths (in the range of 1.8 to 2.2 tons/ft) for the SS39. This can be attributed to the fact that many of the tests in that range were performed on bolts installed in undersize holes (i.e. 1.375” holes). Nevertheless, general conclusions which are drawn for SS39 bolts should hold also for SS33 bolts.

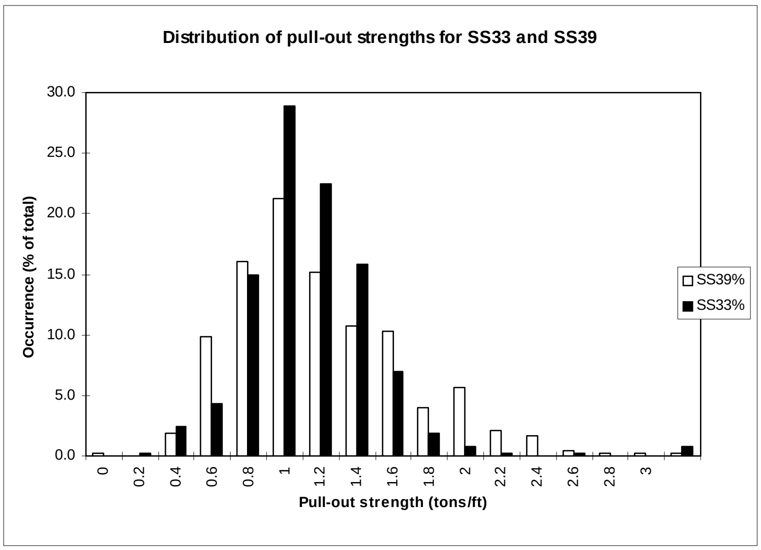

Figure 2-19. Normalized histograms showing the distribution of pull-out strengths for SS33 and SS39 bolts. The sample size is 475 test results for the SS39 and 374 for the SS33.

For the purposes of determining what value of bond strength to use in a deterministic stability analysis or which distributions to assign in a probabilistic analysis, Fig. 2-20 provides a quick and easy reference, provided that the drilling bit size and the rock type are known.

The distributions shown in Fig. 2-20 are for SS39 bolts. Distributions for SS33 bolts should be qualitatively similar, i.e. a 1.3 inch bit for the SS33 corresponds roughly to the 1.5 inch bit for the SS39.

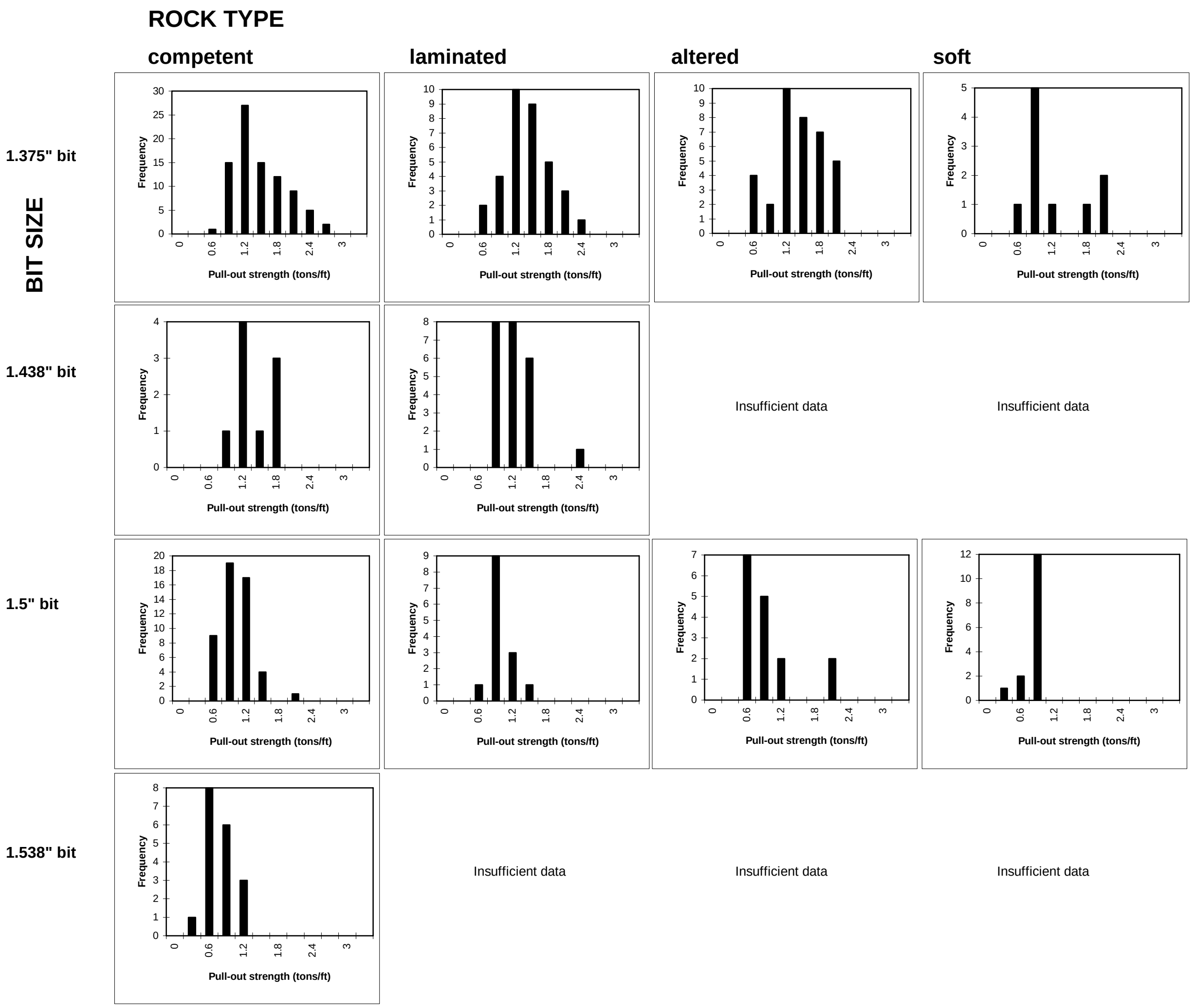

Figure 2-20. Histograms showing the distribution of immediate pull-out strength for different rock types and bit sizes. Note that the sample sizes are not all the same and that there was not enough data in some circumstances to produce histograms. All histograms are for SS39 bolts.

As is shown, the distributions of pull-out strength values for all rock types shift to the left progressively with increasing bit size. The mean values for each distribution are plotted as curves in Fig. 2-8. Note that the distributions presented in Fig. 2-20 are for pull tests conducted immediately or very soon after installation (less than 6 hours). To account for load development with time, Figs. 2-15 and 2-16 show the shift to the right which occurs in the distributions with time.

Several concerns need to be met during the ground support design process; first, that the installed Split Set possesses sufficient bond strength immediately after installation to support the excavation; second, that load development with time does not cause rupture of the steel (if support is intended for a period longer than several days). An optimum solution must be found.

An example of a simple design method is as follows:

1. The first step is to identify the length of time for which the Split Set is intended to provide support (i.e. is the design scenario temporary sidewall support in a shaft sinking operation or is it long-term support for burst-prone gound, etc…)
2. The second step is to identify the rock type and refer to the load development charts and distributions to get an idea of what anchorage increases are expected in the design time frame. (see Figs. 2-12 to 2-16).
3. Establish a desired initial bond strength which will not result in long-term steel failure.
4. Knowing rock type and the desired initial anchorage, the fourth step is to recommend a drilling bit size based on the distributions shown in Fig. 2-20 or the generalized curves shown in Fig. 2-8.
5. Having established the expected value or distribution of bond strength, the next step is to specify a bolting pattern, with a density that is sufficient to support expected loads.
6. After bolt installation has begun, design assumptions can be compared to actual performance values using Figs. 2-5 and 2-6 if drive times are measured or to periodic pull test results.

The distributions presented in this paper form the basis for the data to be used in a probabilistic analysis. In such an analysis, uncertainty is taken into account and a resulting support reliability (expressed in terms of percentage) can be determined. An example of such an analysis is presented in Tomory et al. (1997).

2.7.0 CONCLUSIONS

One of the primary benefits from an undertaking such as the one presented in this paper is that the findings are derived empirically from actual field test data. As mentioned in the introduction, one of the key obstacles in rock engineering design is a general lack of information concerning rock mass behaviour and rock-support interaction. The current research has attempted to address the latter of the two by considering the effects of various factors on the bond strength of a particular type of supporting element - the Split Set.

The two most important factors governing the immediate strength of installed Split Sets are rock type and bit size. Additionally, with time after installation, the strength increases at different rates for different rock types. Figures have been presented in this paper that should enable mine engineers to determine the expected value of pull-out strengths given bit size and rock type and time elapsed after installation. The result should be safer, more efficient and more economical support designs for Split Set applications.

For example, given a certain rock type, ground support designers can refer to the relationships presented in the various figures of this report to determine the anticipated bond strength for bolts installed in holes of various sizes. Additionally, bolt load, or bond strength, development has been analyzed and can be factored into drilling bit selection if there is a final desired long-term load for the Split Set. Finally, Simple indications of strength can be obtained by measuring the drive time and referring to the chart provided in this paper.

The results presented in this paper are ideally suited to probabilistic analyses where distributions for Split Set bond strength can be defined for many operating conditions. For instance, if rock type, drilling bit size and time after installation are known, there are several distributions which could be applied. Further discussion on the probabilistic and statistical aspects of the data presented herein will be discussed in subsequent chapters.

Finally, it is the hope of the authors that further studies, similar to this one, will be undertaken for other types of ground support. In this report, only the Split Set bolt has been considered, partly because it is perhaps the supporting element with the most easily quantified and measured strength. Nevertheless, comparable studies considering resin-grouted bolts, cable bolts, mechanically-anchored bolts and all other types of supporting elements would be welcome additions to the rock engineering and ground support design process.

2.8.0 ACKNOWLEDGEMENTS

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