ANALYSIS OF SWELLEX BOLT PERFORMANCE AND A STANDARDIZED ROCKBOLT PULL TEST DATASHEET AND DATABASE

by

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A thesis submitted in conformity with the requirements
for the degree of Master of Applied Science
Graduate Department of Civil Engineering
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ABSTRACT

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An extensive study was conducted to determine the effects of rock mass parameters and operational parameters on the performance of Swellex rock bolts, wherein pull test data was compiled from various mines in North America and Europe. The data was statistically analysed, and the results, which quantify the influence of various factors on the performance of the Swellex bolt, were evaluated. A set of recommendations was formulated in order to assist in the practical design and efficient use of Swellex bolts.

Little pull test data existed concerning Swellex bolts, and the information available was non-standardized. Therefore, a form was developed to assist in the standardization of the pull test information that is recorded and a database was created to house pull test data. The form and database will be widely available for use by mining engineers. In time, the database will become and invaluable tool in the design of rock bolt support.

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1

INTRODUCTION

The lack of available information concerning the behaviour of a rock mass and its interaction with the rock support system is a common problem encountered by many mining and rock mechanics engineers when using rock bolts in rock support design. The research conducted in this thesis concentrates on the performance of Swellex friction anchored rock bolts under mining conditions. Swellex bolts are used as a means of rock support in many underground mines in North America and Europe. In order to study the influence of rock mass and operational parameters on the performance of these bolts, an extensive study was conducted, wherein pull test data was compiled from various mines in North America and Europe. The data was then statistically analysed and the results were discussed. Parameters that influenced the performance of the Swellex bolt are identified in the first section of this thesis.

The second section of this thesis relates the influencing factors to the installation of the bolt. It also explains the reason for their influence. A sensitivity analysis with respect to these factors was conducted. Based on the results of the first section and the sensitivity analysis, a set of recommendations and considerations were formulated in order to assist mining engineers in the practical design and efficient use of Swellex bolts.

The third and fourth sections arose out of the first section. Through the course of the research, it became apparent that very little pull test data existed for Swellex bolts. The information that was available was not standardized. The combination of insufficient and non-standardized data made analysis extremely difficult. The same problem was also encountered by Mr. Paul Tomory at the University of Toronto, in his research into the performance of Split Set bolts.[1] A two-part solution to the two problems was devised.

The first part of the proposed solution, and the third section of this thesis, is a form that was developed to assist in the standardization of the pull test information that is recorded. This form integrates the type of pull test information and the format in which it is commonly recorded, with the standards recommended by the ASTM and ISRM, and with the results of the first two sections of this thesis. This form will be available in a widely accessible location so that mining engineers who conduct pull tests will be able to access and use the form.

The second part of the proposed solution is a database that was developed to house pull test results for all types of rock bolts. It contains the data that was gathered for this thesis, the research into the performance of Swellex bolts, and from previous research done at the University of Toronto on the performance of Split Set bolts.[1] In all, there are more than 1200 pull test records in the database. The database will also be widely accessible and available for use by mining engineers to aid in the design and efficient use of rock bolt support. The database will be promoted and the mining community will be encouraged to expand the database by contributing the results of future pull tests to the database. The database will be updated and expanded periodically to include this new information. In time, the database will become an invaluable tool in the design of rock bolt support.

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[1] Tomory, P., Analysis of Split Set Bolt Performance, University of Toronto, 1997

2

FACTORS INFLUENCING THE PERFORMANCE OF SWELLEX ROCK BOLTS UNDER MINING CONDITIONS

2.0 SUMMARY

Many underground mines use Swellex bolts for rock support. Thus far, little research has been conducted into the effectiveness of Swellex bolts in actual mining conditions. The bolt manufacturers supply most of the performance data that is available, and the tests are generally conducted in carefully controlled "laboratory" conditions. The strength of a Swellex bolt is measured through the use of a pull testing apparatus, which generally involves an apparatus to apply a jacking force on the bolt as well as a gauge to measure the applied force. The load at which the bolt is pulled or slips out of the hole is called the ultimate load and is measured in metric tonnes. Generally, this number is divided by the length of the bolt. The resulting value is the pullout resistance.

A study was conducted into the performance of Swellex rock bolts under mining conditions in order to analyse the effects of operational parameters and rock mass parameters on the performance of the bolts. Over 300 pull tests records were collected from mines in North America and in Europe. A variety of ground condition parameters including lithology, UCS, Young's Modulus, RMR, RQD and water level parameters, were investigated. As well, information for operational parameters such as pump pressure, drill bit diameter and drilled hole diameter was gathered. Additionally, residence time data (time between installation of the bolt and the testing date) and corrosion level data were gathered for each test. Not all tests included information for all of the parameters. In fact, there was a large disparity in the information that was recorded from mine to mine. The information was made as complete as possible. Statistical analyses were conducted and several charts, which attempt to quantify the influence of each of the operational and rock mass parameters on the pullout resistance and ultimate load, were produced. Trends in the charts were identified and the influence of each of the parameters on the performance of the bolt was evaluated.

2.1 INTRODUCTION TO SWELLEX BOLTS

Swellex is a friction anchored rock bolt and is manufactured and distributed by Atlas Copco Ltd. in North America. Friction-anchored bolts transfer the load from the rock directly to the anchor without the aid of either a bonding agent or a mechanical locking device. The anchorage is generated in the Swellex bolt via the compression of the rock surrounding the bolt during inflation of the bolt, and the resulting elastic rebound of the rock onto the bolt when the inflation pressure is released.

Swellex was introduced to the mining industry over twenty years ago. Today, Swellex is a commonly accepted form of temporary support in mining operations around the world. The vast majority of the Swellex market is in Europe and Quebec. The bolt is used more extensively in Europe than it is in North America. It is particularly popular in tunneling operations in countries such as Switzerland, Germany and Italy. It is also used in Asia when fast economical support is required. Swellex is the preferred product in these operations because the installation is fast and quality control is assured through the pump pressure. Swellex is also starting to break into the market in Manitoba and the United States, particularly in Nevada. It also has a significant presence in Ontario and is used in the Raglan Mine and Louvicourt Mine as well as by mining companies such as Agnico-Eagle Properties Ltd. and Barrick Gold Ltd., in Ontario mines.

Swellex is most often used as a temporary form of support, from 6 months to a year. Corrosion is the primary cause of degradation of the bolt. In low corrosion environments it can be used for up to ten years before corrosion affects the performance of the bolt. In highly acidic environments the life expectancy of a bolt is less than two years. When it was first introduced to the market, Swellex had some difficulty with corrosion. Atlas Copco Ltd. developed Coated Swellex to combat this problem. Generally, Coated Swellex is used for permanent support applications.

The Swellex system consists of a rock bolt made of a circular steel tube, which has been folded to reduce its diameter, a face-plate, and a high-pressure water pump. The Swellex system provides immediate axial friction throughout the entire bolt length and mechanical anchoring is provided by a radial mechanical lock. The installation is a straightforward process. The Swellex bolt is placed in a borehole with a diameter of 32-39 mm. A water pump is used to inject high-pressure water into the Swellex tube. The high internal water pressure then inflates the tube, causing the rock mass surrounding the bolt to deform elastically. When the preset pressure has been reached, the mechanical interlock with the rock is achieved.

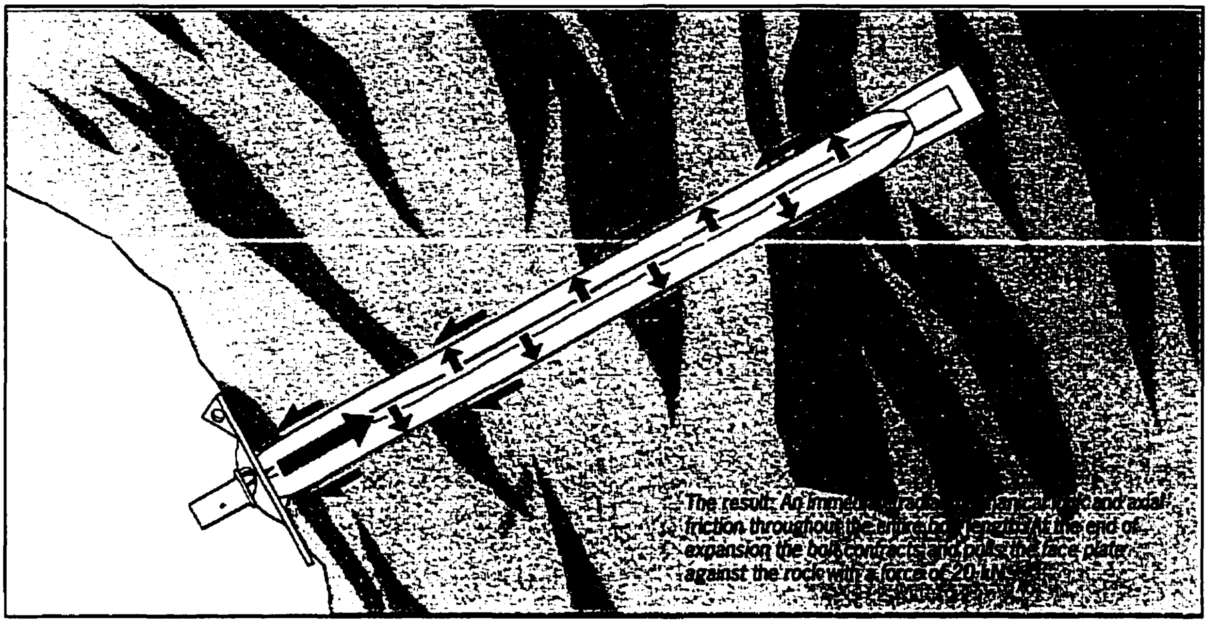

FIGURE 2-1: INSTALLED AND INFLATED SWELLEX BOLT DEMONSTRATING THE ANCHORAGE MECHANISMS[2]

During the expansion process, the Swellex bolt compresses the material surrounding the hole and adapts its shape to fit the shape of the hole. The combination of frictional and mechanical locking effect is generated throughout the entire length of the bolt.[3]

Traditionally, rock bolts were limited to use in reasonably competent rock. Swellex bolts are breaking new ground in this area. They have been designed to perform better than any other bolt under adverse rock conditions. "Swellex bolts reinforce and improve the condition of the surrounding rock and increases its load-bearing capacity. The pressure exerted during installation compresses the rock surrounding the borehole and increases the friction along the bolts making them an integral part of the supporting arch."[4]

2.1.1 Types of Swellex Bolts

Atlas Copco Ltd. distributes a wide range of Swellex bolts. The bolts are designed to fit holes from 32 to 52 mm in diameter, and from 1.2 m to 8 m in length. Different bolts are designed for use under

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[2] Atlas Copco Ltd., Swellex Product Manual, Swellex – The Engineered Rock Reinforcement System, p.3

[3] Ibid.

[4] Ibid.

different conditions. The main bolt types are summarised below along with their capacities, dimensions and the conditions for their intended use.

<table>
<tr><th>Type of Swellex</th><th>Diameter, Thickness</th><th>Capacity</th><th>Pump Pressure</th><th>Borehole Diameter [5]</th></tr>
<tr><td>Standard Swellex</td><td>41 mm, 2 mm</td><td>100 kN</td><td>30 MPa (4350 psi)</td><td>32 mm to 39 mm</td></tr>
<tr><td colspan="5">Comments: The physical properties of the steel used provide a margin of safety. The unique load displacement characteristics, and the ability to accommodate large rock movements without decreasing its bearing capacity make the bolt ideal for conditions in which large ground movements are anticipated.</td></tr>
<tr><td>Midi-Swellex</td><td>54 mm, 2 mm</td><td>120 kN</td><td>24 MPa (3480 psi)</td><td>43 mm to 52 mm</td></tr>
<tr><td colspan="5">Comments: Lighter version of the Super-Swellex bolt. The bolt can accommodate elongation of up to 20%, which means it is designed not to fail when it reaches it tensile strength but instead to deform to accommodate large rock movements.</td></tr>
<tr><td>Super-Swellex</td><td>54 mm, 3 mm</td><td>200 kN</td><td>24 MPa (3480 psi)</td><td>43 mm to 52 mm</td></tr>
<tr><td colspan="5">Comments: The capacity of this bolt is 200 kN and is useful in applications where high breaking loads and demands for increased safety and speed are at a premium.</td></tr>
<tr><td>Yielding Swellex</td><td>54 mm, 3 mm</td><td>160 kN</td><td>30 MPa (4350 psi)</td><td>43 mm to 52 mm</td></tr>
<tr><td colspan="5">Comments: It has the capacity to elongate up to 30% which means that it doesn't fail when it reaches it tensile strength, but deforms to accommodate extremely large rock movements.</td></tr>
<tr><td>Coated Swellex</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="5">Comments: All of the Swellex products are available in corrosion resistant version, through the use of a special corrosion protection coating.</td></tr>
</table>

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[5] Atlas Copco Ltd.

2.1.2 Cost of Swellex

Swellex is a low cost alternative for temporary support, which is the reason why it is preferred in tunneling operations where low cost methods of short term support are required. A study was conducted into the comparative costs of Swellex vs. other rock anchors.[6] The purchase price of the bolt as well as the associated drilling costs, installation costs were calculated and an overall cost of the bolt was determined. The cost per bolt was then standardized by the length of the bolt and the capacity to yield a unit cost of $CAD/ft/T. A summary of the results is shown in Table 2-1. A graph showing the total and component costs of each of the bolts is shown in Figure 2-1.

TABLE 2-1: COMPARATIVE COSTS OF DIFFERENT BOLT TYPES

Canadian Market – 2 Person Operation – Manual Drilling – Bolts not longer than 2.4 m						
Calculation at (per hour) 60.00 $		Purchasing $CAD/ft	Drilling $CAD/ft	Installation $CAD/ft	Total Cost $CAD/ft	Capacity Cost $CAD/ft/T
Bolt Type	Capacity (T)					
Mechanical	7	0.86	1.24	0.15	**2.25**	**0.32**
Split Set	6	1.28	1.24	0.29	**2.80**	**0.47**
Resin Rebar	18	1.66	1.24	0.79	**3.69**	**0.20**
Coated Standard Swellex	11	2.08	1.24	0.16	**3.48**	**0.32**
Standard Swellex	11	1.65	1.24	0.16	**3.05**	**0.28**
Williams Cement	20	1.80	0.83	4.50	**7.13**	**0.36**
Dywidag Resin	22	2.70	0.83	0.75	**4.28**	**0.19**
Super Swellex	20	4.00	1.60	0.31	**5.91**	**0.30**
Cable bolt (4.0 m)	25	1.40	1.60	4.50	**7.50**	**0.30**

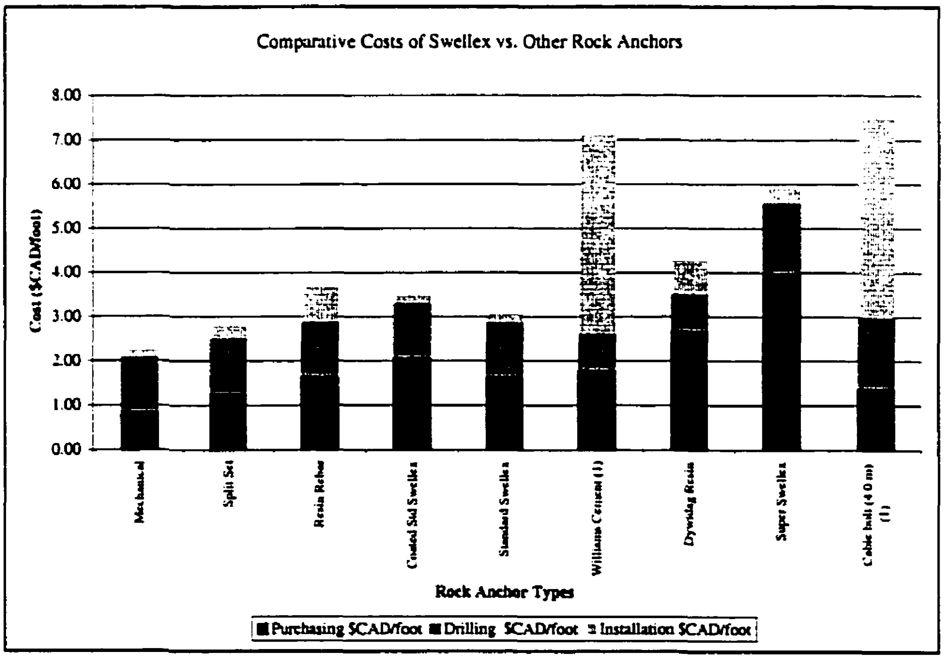

FIGURE 2-2: COMPARATIVE COSTS OF SWELLEX VS. DIFFERENT BOLT TYPES

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[6] Charette, F, Hadjigeorgiou, J, Guide Pratique du Soutènement Minier, Association Minière du Québec, 1999

2.2 PULL TESTING

There are essentially two main categories of standard pull tests that can be performed on Swellex bolts to determine the load-bearing capacity of the bolt system: destructive and nondestructive tests. Destructive tests can have one of two outcomes, either the bolt breaks (in which case it is referred to as a broken test), or the bolt slips out of the hole (in which case it is referred to as a slipped test). The three types of tests are described below: nondestructive, broken and slipped tests.

2.2.1 Nondestructive Pull Tests

The pull test equipment is assembled and fitted to the bolt that is to be tested. The hand pump is operated until the specified pullout load is attained. A maximum of 9 tonnes is recommended for Standard Swellex in order to assure that the bolt does not break. The person conducting the test, who decides the load at which the test will be stopped, controls the results of a nondestructive test. The nondestructive tests are only indicative of a minimum load bearing capacity of the bolt.

2.2.2 Destructive Tests

The pull test equipment is assembled and fitted to the bolt. A hand pump is used to apply a jacking pressure to the bolt. The pressure is applied until the Swellex bolt either slides out of the hole or breaks in the hole.

Broken Tests

When the bolt breaks as a result of the failure of the steel, the test is referred to as a broken test. Atlas Copco Ltd. suggests that the minimum load at which the bolt will break is 100 kN or 10 tonnes. Stillborg, in his research into the load-deformation characteristics of different rock bolts in tensile loading across a joint, states that this minimum load at which the bolt will break is 110 kN or 11 tonnes.[7]

Slipped Tests

When the bolt is pulled out of the hole, the test is called a slipped test. Atlas Copco Ltd. suggests that a deformation of more than 15 to 25 mm ensures that the bolt is slipping.[8] Stillborg and others suggest this minimum deformation occurs at 10 mm (see Figure 2-4). There were only seven pull test records with deformations that between 10 to 15 mm. Because a relatively small number of records were affected by a conservative criterion, the 15 mm criterion was used in this study to ensure that

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[7] Stillborg, B., Rockbolt Loading Across a Tensile Joint, Lulea University of Technology, Sweden

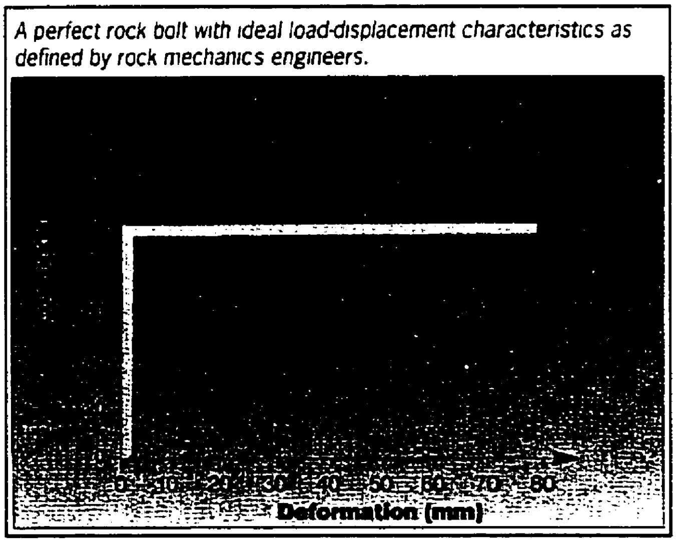
tests were not mistakenly classified as slipped, when in fact they were not. Atlas Copco Ltd. states that the capacity of the Standard Swellex bolt is 100 kN or 10 tonnes. This is the load at which the slip should begin to take place.

2.2.3 Ultimate Load and Pullout Resistance

Ultimate load is the load in metric tonnes at which the test is stopped in a nondestructive test. In destructive tests, it is the load at which the bolt breaks in a broken test, or where the bolt slips out of the hole in a slipped test. Again, the bolt is considered to be slipping at a deformation of more than 15 mm. The pullout resistance is calculated by dividing the ultimate load by the overall length of the bolt and is measured in tonnes/m.

2.2.4 Ideal Load Deformation Curve

The model of an ideal rock bolt acting across a single joint in tension would have the load displacement characteristics shown in Figure 2-3. This relationship would be independent of ground stress conditions and rock mass conditions. The bolt should initially be infinitely stiff in order to draw as much load as possible from the rock mass on to the rock bolt. Ground deformation should result in immediate and full bearing capacity of the bolt. When the load on the bolt approaches the ultimate tensile strength of the bolt, the bolt should deform perfectly plastically to accommodate ground deformation while maintaining its load bearing capacity.[9]


A perfect rock bolt with ideal load-displacement characteristics as defined by rock mechanics engineers.

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[8] Personal communication with Atlas Copco Ltd. Product Support Personnel, Francois Charette

[9] Stillborg.

FIGURE 2-3: IDEAL LOAD-DISPLACEMENT CHARACTERISTICS OF AN INSTALLED ROCKBOLT (FROM ATLAS COPCO PRODUCT MANUAL)

2.2.5 Load-Deformation Characteristics of the Swellex Bolt

The load deformation characteristics of the Swellex bolt are shown in Figure 2-4 and 2-5. Figure 2-4 is the load-deformation curve of the Swellex bolt from the Atlas Copco Ltd. Product Manual. Figure 2-5 is the load deformation curve for Swellex bolt, as provided by Stillborg in his research into the load-deformation characteristics of different rock bolts in tensile loading across as joint.

Initially, no deformation occurs in the rock bolt until the yield point is reached. The Swellex EXL maintains a constant to increasing load-bearing capacity for the duration of the test.

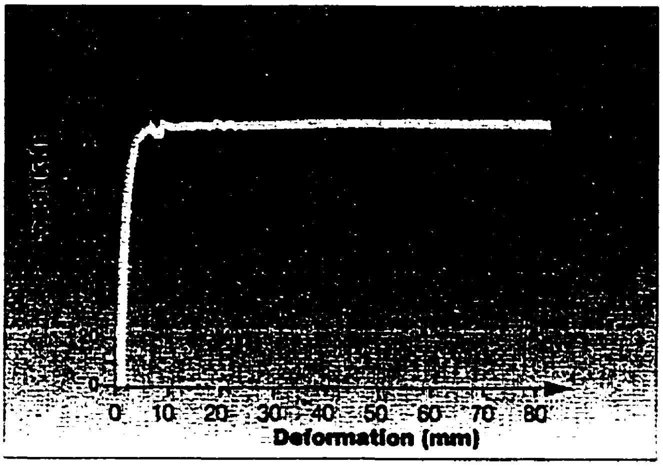

FIGURE 2-4: LOAD-DEFORMATION CHARACTERISTICS OF THE SWELLEX BOLT (FROM ATLAS COPCO PRODUCT MANUAL)

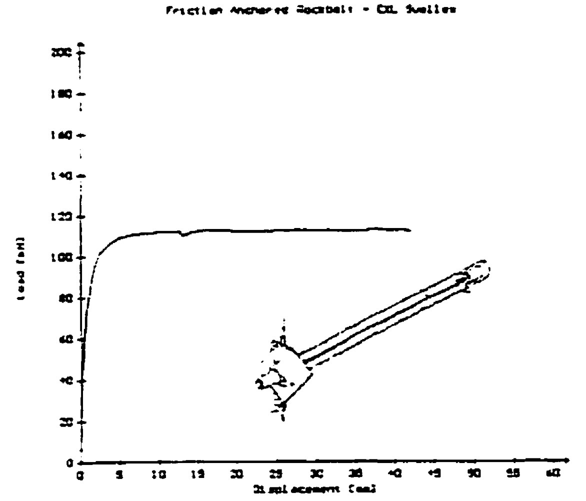

Fig. 15 Friction anchored rockbolt - Swellex, type EXL, tensile loading across a joint.

FIGURE 2-5: LOAD-DEFORMATION CHARACTERISTICS OF THE SWELLEX BOLT (FROM STILLBORG)

Stillborg conducted an investigation into the pull test behaviour of various types of rock bolts. One of the tests was performed on a Swellex bolt which was 3 metres in length, with a borehole diameter of 37 mm, inflated at 30 MPa, with an ultimate tensile strength of the steel tube before inflation of 110 kN or 11 tonnes. The bolt began to deform at a load of 50 kN, 5 tonnes. Bond failure commenced as a result of this deformation. The axial elongation caused the lateral contraction of the bolt and the bolt separated from the rock interface progressively along the length of the bolt. In the process, frictional and interlocking resistances were overcome. The bond failure continued as the load approached the ultimate tensile strength of the steel. At 115 kN, which corresponded to a deformation of 10 mm, the bond had completely failed and the bolt began to slide. However, it maintained its load bearing capacity as it continued to slide.[10]

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[10] Stillborg.

2.3 DATA COLLECTION

The data was collected over a period of 18 months. The collection process involved contacting rock mechanics specialists at each mine in Ontario and in the other provinces in Canada via phone or e-mail. The Canadian Mines Handbook was used as a directory and each of the mines in the Handbook were contacted individually. The Canadian Mining Journal was also used as a resource. The Canadian Mining Journal conducts a survey every year of the different support methods used by each of the mines in Canada. The mines which indicated that they used Swellex were contacted first. As the Journal's survey is not exhaustive, and not all mines responded to the survey, it was used only as a cross-reference.

It became apparent that there was very little Swellex pull test data available. There were a number of reasons for this. When the ground control people at the mines were contacted they were asked whether or not the mines used Swellex rock bolts as a support method. A rather small percentage of mines in Canada use, or have used, Swellex bolts as a support method. It is estimated (from the results of this data gathering effort) that 10% to 15% of the mines use Swellex. If Swellex bolts were used by the mine, the pull test results were requested. Not many of the mines that use Swellex performed pull tests. Of those who did, some could not locate the information, further reducing the pool of available data. Considering the mobility of ground control specialists within the mining community, it is not surprising that the data was sometimes lost. Those mines which did have available, pertinent data, sent the data by mail, fax or by e-mail.

The other source of information was the Swellex manufacturer, Atlas Copco Ltd. Although Atlas Copco Ltd. was unwilling to provide a customer list, they did provided some data that covered the last five years of pull testing that the Montreal office of Atlas Copco Ltd., had conducted. Some of these data points included data from Europe, particularly in Sweden, Germany and Italy, where the use of Swellex bolts is more popular.

The pull test results were often incomplete or did not contain sufficient and/or pertinent data. In some cases, the length of the bolt was not recorded. In other cases, the ground conditions, the residence time or the diameter of the hole was not recorded. The second step in rounding out the collected data involved contacting the ground control personnel again and asking them if they could supply this additional information. In some cases, the mines supplied ground condition reports and maps of the drill locations, as well as drill cores taken in the area.

2.4 DATA ANALYSIS

Once all possible measures to fill in gaps in the information and to gather as much data as possible were exhausted, the data was catalogued and sorted. A number of items for each pull test were recorded:

- ☐ Bolt specifications:
    - ☐ type of rock bolt, Standard Swellex, Super Swellex or Coated Swellex
    - ☐ length of the bolt

- ☐ Installation parameters:
    - ☐ diameter of the hole
    - ☐ size of the drill bit
    - ☐ pump pressure
    - ☐ installation date
    - ☐ date of the pull test
    - ☐ time between installation and pull test
    - ☐ inflation time

- ☐ Ground conditions parameters:
    - ☐ RQD
    - ☐ RMR
    - ☐ Q
    - ☐ UCS
    - ☐ elastic modulus of the rock
    - ☐ type of rock, shear zones, tensile zones
    - ☐ location of the hole

- ☐ Characteristics of the pull test itself:
    - ☐ destructive, nondestructive or if slipping had occurred
    - ☐ comments about the failure mode and location of the failure
    - ☐ pull out load, pull out load per metre of bolt
    - ☐ amount of deformation (displacement at specific load)

Not all of the pull test records included information about all of the different parameters. In fact, most pull test records contained information for only 4 to 8 of the 20 parameters. A significant amount of interpretation was required for most of the pull test records. For example, different units were used from record to record, so units were converted to a selected standard. Also, the type of pull test (i.e., nondestructive, broken or slipped), was rarely stated explicitly. This information had to be interpreted from the testers' comments and from the deformation information.

About 4 passes at the complete set of records was required in order fully understand each of the records. The first pass involved simply recording the information in the pull test records in a large spreadsheet, with each of the parameters as a column and each of the pull test records as a row. The second pass required further reading and assembling more information from the mines. The third pass, required the interpretation of the data, including classifying the data by test type. This interpretation of the data was not done in the first pass because a full understanding of the different pull test results was not obtained at this point. The term *destructive test*, or *failed bolt* was often used. For Swellex bolts, these terms mean that the bolt broke, and not that the bolt had slipped. This was not initially understood, as a failed test normally means that a bolt had slipped for all other rock bolts types, and so the tests had to be reclassified a fourth time with this in mind. The criterion for slipping (see Section 2.2.2) was also developed at this point and used to classify the data. This task was extremely difficult and time-consuming. It would have been much simpler if a standard terminology was developed and used to record pull testing information.

As mentioned previously, one of the results of this thesis was the generation of a standardized form, which will aid in the recording of all pertinent information. This would create a standard in the industry and ensure that all the pertinent information would be recorded every time a pull test is conducted. Another result of this thesis was a database of the information that has been recorded thus far, which can be accessed by the public.

2.5 DISTRIBUTION OF PULL TESTS BY BOLT TYPE AND PULL TEST TYPE

2.5.1 Selection of Dataset

A total of 309 pieces of data were collected. However, 5 tests were missing vital information and were eliminated, for a net result of 304 useable test records. This data included pull test results from all of the four main types of Swellex bolts (Standard Swellex, Super Swellex, Coated Swellex and Yielding Swellex), and for the three types of tests (broken tests, nondestructive tests, and slipped tests). The majority of the data was for Standard Swellex. The distribution of pull test data is shown in Table 2-2.

TABLE 2-2: DISTRIBUTION OF SWELLEX PULL TEST DATA BY BOLT TYPE AND BY TEST TYPE

Test Type	Swellex Bolt Type				
	Standard Swellex	Coated Swellex	Super Swellex	Yielding Swellex	All Swellex Bolt Types
Broken	42	0	4	1	**47**
Nondestructive	60	4	4	0	**68**
Slipped	173	2	7	7	**189**
All Test Types	**275**	**6**	**15**	**8**	**304**

It is apparent that there is an insufficient amount of data for many of the combinations. There were 47 tests where the bolt broke and 68 nondestructive tests. When these tests are segregated by bolt type category, a valid statistical analysis could not be performed for many of the combinations of test type and bolt type. Standard Swellex was the only combination where there was a sufficient amount of data to perform a valid statistical analysis. Therefore, this study concentrated on the Standard Swellex pull tests only, a total of 275 from the original 304 tests.

2.5.2 Anomalous Data

There were 10 data points in which unusually high loads were recorded, 18 to 25 tonnes. The yielding strength of the steel in a Swellex bolt is well below 18 tonnes. This data all came from one source, and because the ultimate loads were more than were 50% higher than any of the other pull test records, the results were considered unreliable and were eliminated from the dataset, (for all of the parameters except for Pump Pressure, see Section 2.8.3).

2.5.3 Summary of the Pull test Information Gathered in the Research

A breakdown of the data collected in this study is provided in Table 2-3. A complete analysis of the pattern of information that is recorded in pull tests is provided in Section 3. However, it is important to note the lack of information in many of the parameters, particularly the information with respect to the ground conditions. These numbers reflect the data gathered *after* the mines had been contacted to fill out the information. The numbers were even lower for the data prior to the second data gathering effort. Even basic information such as drill bit diameter and pump pressure was rather sparse.

TABLE 2-3: BREAKDOWN OF THE PULL TEST INFORMATION GATHERED IN THE STUDY

	All Swellex Bolts		Standard Swellex Bolts							
	All Tests (304 records)		All Tests (275 records)		Slipped (173 records)		Nondestructive (60 records)		Broken (42 records)	
	No. of Tests	% of All Tests	No. of Tests	% of All Tests	No. of Tests	% of Slipped	No. of Tests	% of Nondest	No. of Tests	% of Broken
Bolt & Installation Parameters										
Type of Bolt	304	100	275	100	173	100	60	100	42	100
Length of Bolt	276	91	248	90	148	86	59	98	41	98
Drilled Hole Diameter	183	60	183	67	129	75	25	42	29	69
Drilled Bit Diameter	51	17	51	19	23	13	18	30	10	24
Pump Pressure	97	32	97	35	68	39	6	10	23	55
Inflation Time	4	1	0	0	0	0	0	0	0	0
Location of Bolt	191	63	191	69	126	73	45	75	20	48
Pull test Parameters										
Ultimate Load	304	100	275	100	173	100	60	100	42	100
Deformation	76	25	59	21	43	25	12	20	4	10
Corrosion Level	65	21	65	24	35	20	19	32	11	26
Time Parameters										
Test Date	188	62	188	68	109	63	58	97	21	50
Installation Date	95	31	95	35	50	29	30	50	15	36
Residence Time	95	31	95	35	50	29	30	50	15	36
Ground Conditions										
UCS	99	33	69	25	34	20	20	33	15	36
Elastic Modulus	26	9	26	9	11	6	10	17	5	12
RQD	57	19	56	20	22	13	24	40	10	24
RMR	41	13	37	13	15	9	16	27	6	14
Q	6	2	6	2	6	3	0	0	0	0
Lithology	159	52	159	58	89	51	44	73	26	62
Water Level	64	21	64	23	33	19	22	37	9	21

2.5.4 Ultimate Load and Pullout Resistance

For Swellex bolts, the most important pull test result is the ultimate load. According to Atlas Copco Ltd., 2 feet of bolt is required to achieve the 10 tonnes load that the manufacturer suggests is the minimum capacity of the bolt. The different lengths of bolt are provided for operational purposes. Though, additional load is gained with a longer length of bolt, the additional load is not normally useable, as the bolt should break long before this upper range of the bolt capacity can be mobilized. For each parameter, the trends were analysed with respect to the ultimate load of the bolt.

The pullout resistance results are also important, since the ultimate load is not independent of the length of the bolt. An increase in bolt length results in an increase in inflated length or anchored length. The relationship between length and ultimate load is a complex one and requires more data to determine. Therefore, the two units of measure of the bearing capacity are used in conjunction, as neither ultimate load nor pullout resistance show the complete picture, in and of themselves.

The results for pullout resistance are less reliable, for many reasons. In a few cases, the length of the bolt was not recorded and the standard bolt length of 2.1 m was assumed for these tests. Also, the recorded length of the bolt was in some cases questionable, since the recorded lengths were different from any of the lengths available from the manufacturer, which would mean that the pullout resistance results would also be questionable. It would appear that the effective length, or inflated length of the bolt, was in some cases recorded, not the overall length. Since the effective length is always shorter than the overall length, in some cases significantly shorter, a very high pullout resistance results. It was not easy to differentiate the particular records in which the pullout resistance was actually the effective resistance.

2.5.5 Broken Tests, Nondestructive Tests, and Slipped Tests

Statistical analyses and charts were plotted for each of the test types: broken tests, nondestructive tests, and slipped tests. The results of nondestructive tests are provided solely as an indicator of the minimum capacity of the bolt. The dominating influence in a nondestructive test is the tester, who determines the load at which the test will terminate. Generally, this value is 10 tonnes, the suggested ultimate load-bearing capacity of the bolt. Any other influences are masked by the influence of the pull tester. Therefore, trend lines for these tests should indicate that the parameter under investigation has no influence on the ultimate load of the bolt. The broken test results indicate the breaking strength of the bolt and also indicate the minimum load bearing capacity of the bolt. Most of the parameters considered will have no influence on the breaking strength of the steel, except parameters which physically affect the bolt itself, such as age of the bolt, presence of water, and corrosion level, (for these parameters, a trend is expected).

The basis of the analysis is the set of data for slipped tests, a total of 173 tests. The slipped tests indicate the maximum load bearing capacity of the bolt. The results of the slipped tests are provided along with the nondestructive and broken tests to provide an overall picture of the performance of the bolts. The data and trend lines for slipped tests are also shown in separate graphs to eliminate the visual clutter and to better identify trends. Where possible, such as for the discrete data like drilled hole diameter and pump pressure, the data for slipped tests was further divided into discrete intervals. The mean and standard deviations were calculated for the intervals. Discrete intervals parameters, such as drilled hole diameter, often have scatter associated with grouping the data into discrete intervals. For example, in the case of drilled hole diameter, the standard intervals are 32 mm, 35 mm and 38 mm (from the associated drill bit sizes). Holes which are 33 mm or 36 mm might have been recorded by the tester as one of the standard sizes, which would influence the ultimate load for this interval. For these parameters, the mean of the intervals were plotted in order to eliminate the scatter. The trend line was fitted through the mean values. As well, the correlation coefficient (R^2) was calculated. However, this coefficient (R^2 for trend line fitted through mean values) is not as reliable a measure of the parameter's influence on the ultimate load.

2.6 DISTRIBUTION OF THE DATA

Histograms and summary statistics for the resulting distributions of the ultimate load for each of the test types are shown in Figures 2-6 through 2-10 and Tables 2-4 through 2-7. Histograms and summary statistics for the resulting distributions of the pullout resistance for each of the test types are shown in Figures 2-10 through 2-13 and Tables 2-8 through 2-11.

2.6.1 Ultimate Load Statistics

FIGURE 2-6: HISTOGRAM FOR ALL TEST TYPES

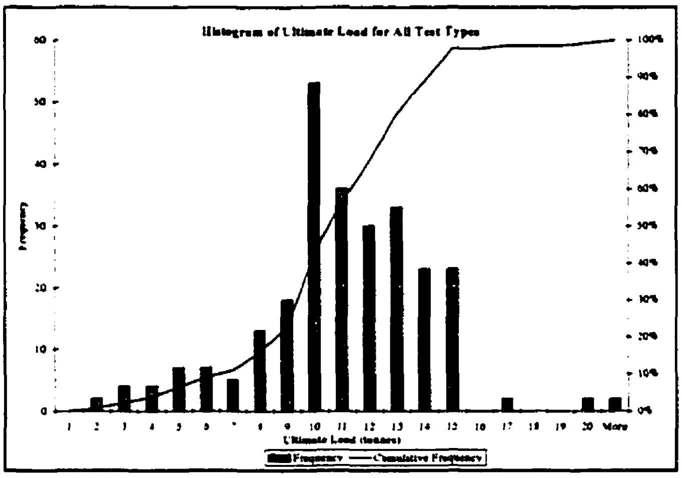

TABLE 2-4: STATISTICS FOR ALL TEST TYPES

Summary Statistics for All Tests	
Mean	10.79
Standard Deviation	3.10
Minimum	1.6
Maximum	21.6
Standard Error	0.19
Median	11.0
Mode	10.0
Sample Variance	9.64
Kurtosis	1.37
Skewness	-0.29
Count	264
Confidence Level (95.0%)	0.38

FIGURE 2-7: HISTOGRAM FOR SLIPPED TESTS

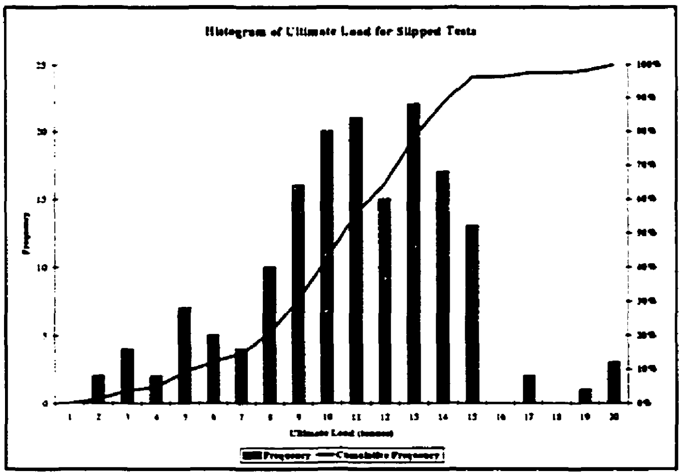

TABLE 2-5: STATISTICS FOR SLIPPED TESTS

Summary Statistics for Slipped Tests	
Mean	10.55
Standard Deviation	3.40
Minimum	1.6
Maximum	21.6
Standard Error	0.27
Median	11.0
Mode	11.0
Sample Variance	11.53
Kurtosis	0.56
Skewness	-0.37
Count	162
Confidence Level (95.0%)	0.53

FIGURE 2-8: HISTOGRAM FOR BROKEN TESTS

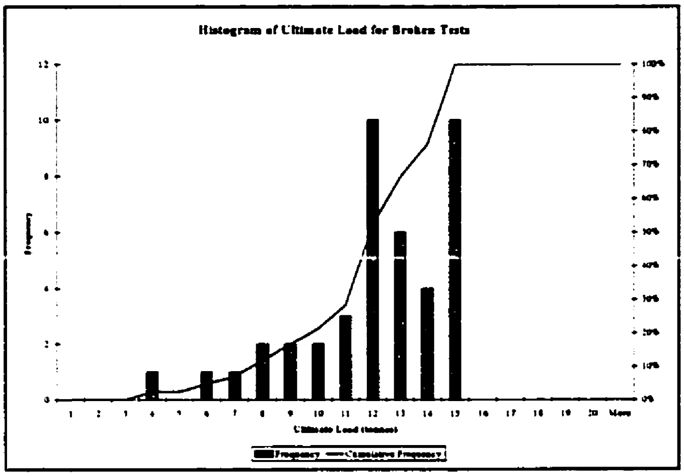

TABLE 2-6: STATISTICS FOR BROKEN TESTS

Summary Statistics for Broken Tests	
Mean	11.73
Standard Deviation	2.71
Minimum	3.5
Maximum	15
Standard Error	0.42
Median	12
Mode	12
Sample Variance	7.36
Kurtosis	1.11
Skewness	-1.14
Count	42
Confidence Level (95.0%)	0.85

FIGURE 2-9: HISTOGRAM FOR NONDESTRUCTIVE TESTS

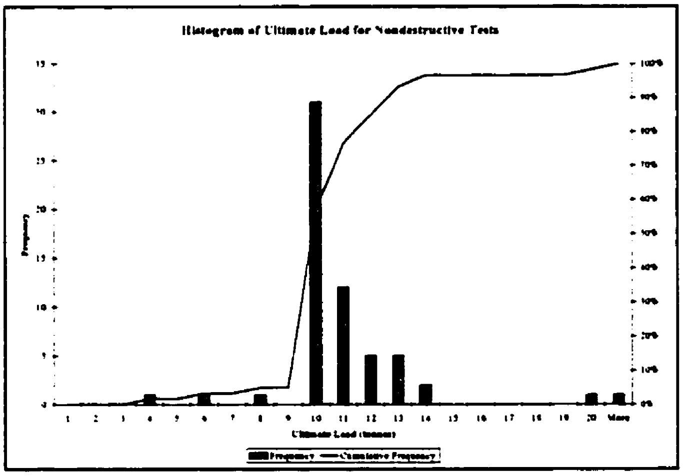

TABLE 2-7: STATISTICS FOR NONDESTRUCTIVE TESTS

Summary Statistics for Nondestructive Tests	
Mean	10.45
Standard Deviation	1.54
Minimum	4.0
Maximum	13.3
Standard Error	0.20
Median	10
Mode	10
Sample Variance	2.38
Kurtosis	5.93
Skewness	-1.45
Count	58
Confidence Level (95.0%)	0.41

The results for all-tests distribution show that the mean is 10.79 tonnes with a standard deviation of 3.10 tonnes. An interesting observation is that about 30% of all of the tests had an ultimate load of less than 10 tonnes, the manufacturer's suggested bearing capacity. These numbers include the effect of the broken and nondestructive tests. The slipped-tests statistics indicate that the mean is 10.55 tonnes with a standard deviation of 3.40 tonnes. About 33% of the bolts that slipped, slipped below 10 tonnes, or 18.5% of the entire dataset (164 records) slipped below 10 tonnes. The broken-test mean is 11.73 tonnes, which is above the 10 tonnes ultimate tensile strength of the bolt. 20% of the broken tests broke below 10 tonnes, or 9 of the 42 that broke. Of all the Standard Swellex bolts tested, 3.4% (9 of 264), broke below 10 tonnes. The nondestructive tests are provided for interest. The effect of these tests are best evaluated in the all test types grouping, as they only provide a minimum bearing capacity, and are not indicative of the maximum bearing (or breaking) capacity.

2.6.2 Pullout Resistance Histograms

The results for all tests show that the mean is 5.81 tonnes/m with a standard deviation of 3.69 tonnes/m. This distribution includes the effect of the broken and nondestructive tests. The slipped test distribution indicates that the mean is 5.93 tonnes/m with a standard deviation of 4.19 tonnes/m. The broken tests distribution indicates that the mean is 6.22 tonnes/m with a standard deviation of 2.29 tonnes/m. This means that the frictional resistance is 6.22 tonnes/m or better. The mean for the nondestructive tests distribution is 5.22 tonnes/m with a standard deviation of 2.90 tonnes/m.

FIGURE 2-10: HISTOGRAM FOR ALL TEST TYPES

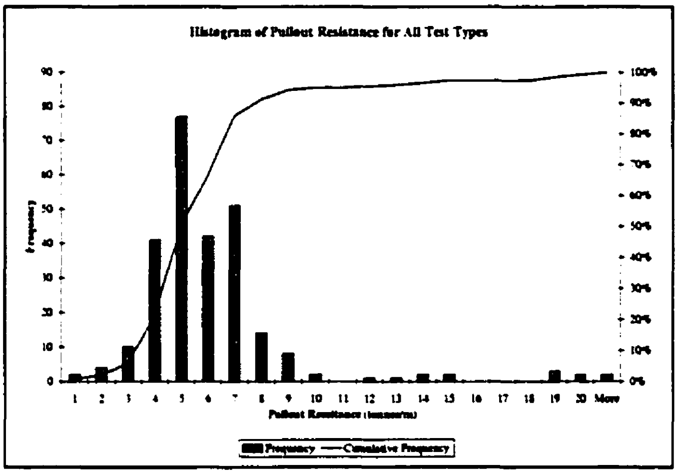

TABLE 2-8: STATISTICS FOR ALL TEST TYPES

Summary Statistics for All Tests	
Mean	5.81
Standard Deviation	3.69
Minimum	0.67
Maximum	36
Standard Error	0.23
Median	5.00
Mode	4.76
Sample Variance	13.58
Kurtosis	29.52
Skewness	4.61
Count	264
Confidence Level (95.0%)	0.45

FIGURE 2-11: HISTOGRAM FOR SLIPPED TESTS

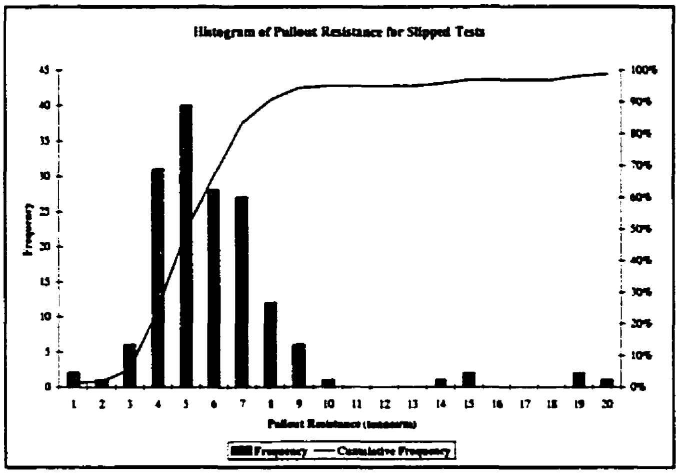

TABLE 2-9: STATISTICS FOR SLIPPED TESTS

Summary Statistics for Slipped Tests	
Mean	5.93
Standard Deviation	4.19
Minimum	0.67
Maximum	36
Standard Error	0.33
Median	5.13
Mode	3.55
Sample Variance	17.59
Kurtosis	27.06
Skewness	4.60
Count	162
Confidence Level (95.0%)	0.65

There is a high degree of variation in the pullout resistance distribution. This may be due in part to the fact that the relationship between length and the ultimate load is not linear. It also may be due to the fact that in some cases the overall length of the bolt was not what was recorded. The length that was recorded was actually the inflated length, which would result in higher pullout resistances. This is the length that should be recorded in all cases. However, it is rarely known. These pullout resistance distributions are provided for primarily for interest. Because of the extremely high anchorage for the Swellex bolt, the influence of the length of the bolt is not easily determined.

FIGURE 2-12: HISTOGRAM FOR BROKEN TESTS

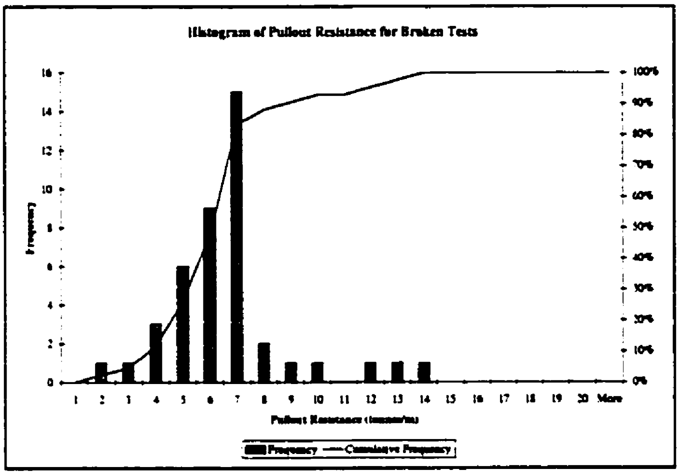

TABLE 2-10: STATISTICS FOR BROKEN TESTS

Summary Statistics for Broken Tests	
Mean	6.22
Standard Deviation	2.29
Minimum	1.67
Maximum	13.51
Standard Error	0.35
Median	6.04
Mode	5.71
Sample Variance	5.22
Kurtosis	2.92
Skewness	1.24
Count	42
Confidence Level (95.0%)	0.71

FIGURE 2-13: HISTOGRAM FOR NONDESTRUCTIVE TESTS

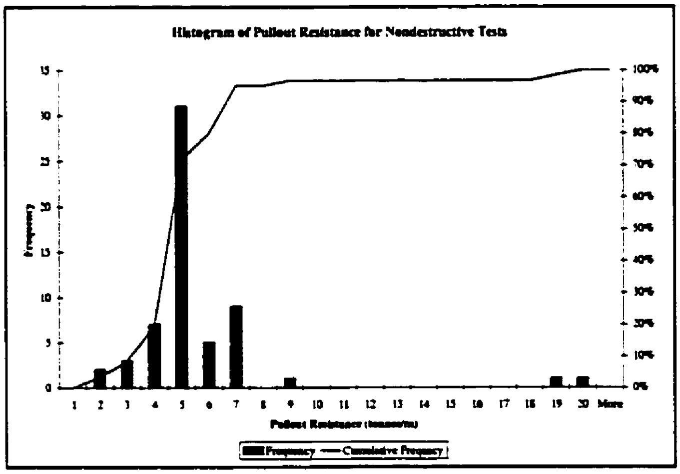

TABLE 2-11: STATISTICS FOR NONDESTRUCTIVE TESTS

Summary Statistics for Nondestructive Tests	
Mean	5.22
Standard Deviation	2.90
Minimum	1.09
Maximum	19.68
Standard Error	0.37
Median	4.76
Mode	4.76
Sample Variance	8.41
Kurtosis	17.59
Skewness	3.82
Count	60
Confidence Level (95.0%)	0.75

2.7 INFLUENCE OF LENGTH

Swellex is available in a range of sizes, from 1.2 m to 8 m in length. In order to assess the influence of the length of the bolt on the ultimate load bearing capacity of the bolt, graphs of the load vs. the length of the bolt were plotted. Linear trend lines were fitted through the data using least-squares linear regression techniques. The correlation coefficients were calculated for each trend line. The results are presented in Figures 2-14 to 2-17.

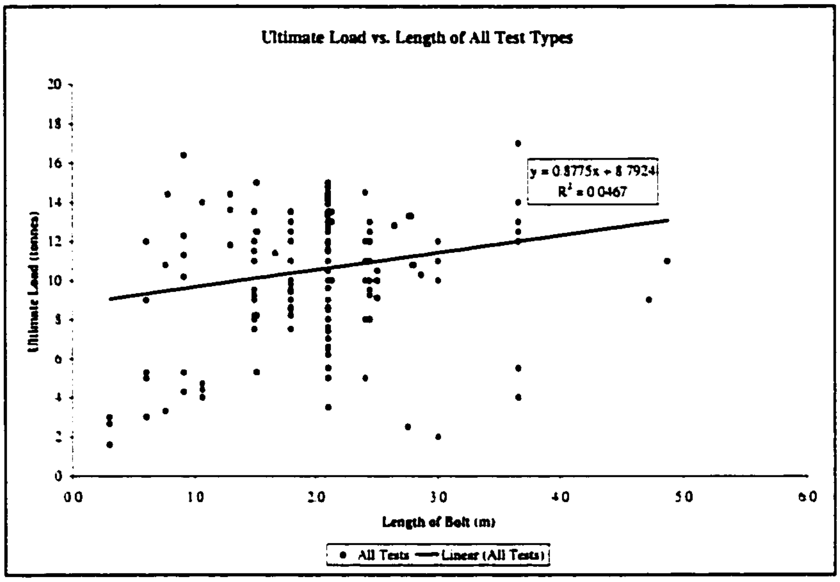

FIGURE 2-14: LENGTH VS. ULTIMATE LOAD FOR ALL TESTS

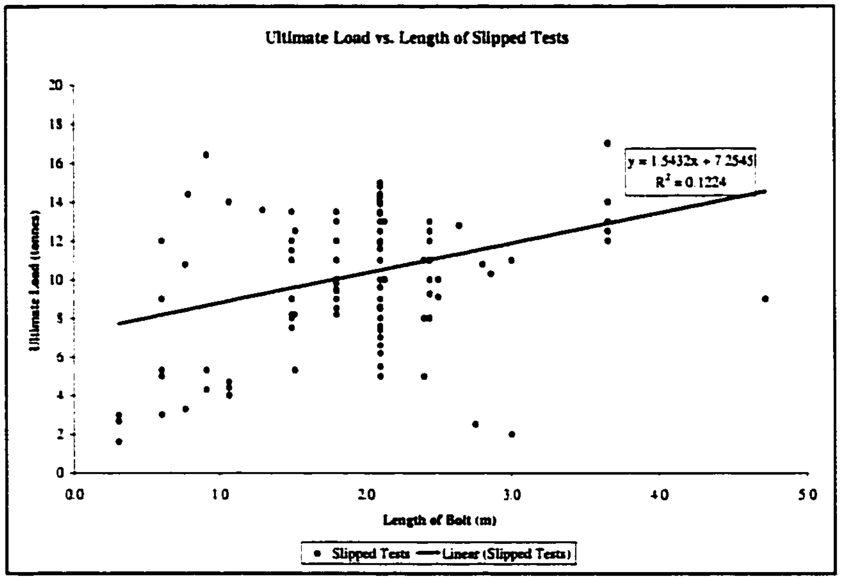

FIGURE 2-15: LENGTH VS. ULTIMATE LOAD FOR SLIPPED TESTS

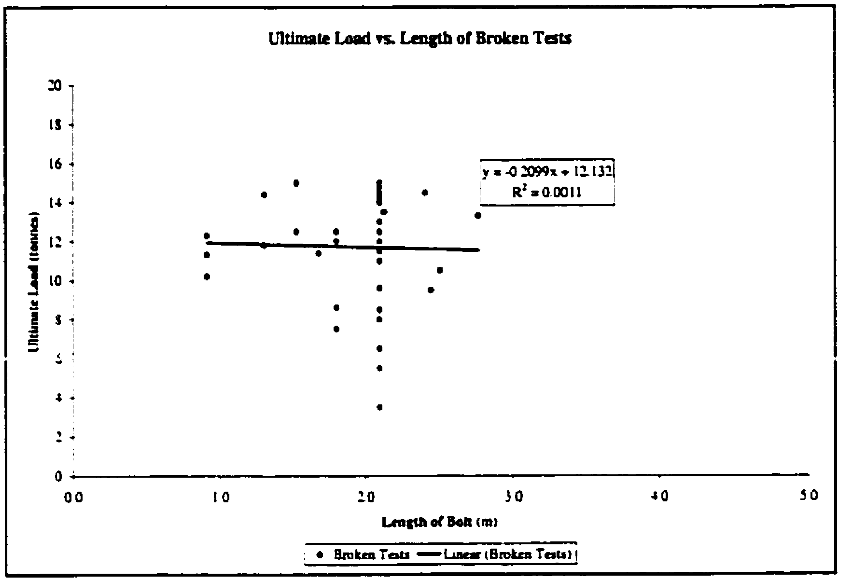

FIGURE 2-16: LENGTH VS. ULTIMATE LOAD FOR BROKEN TESTS

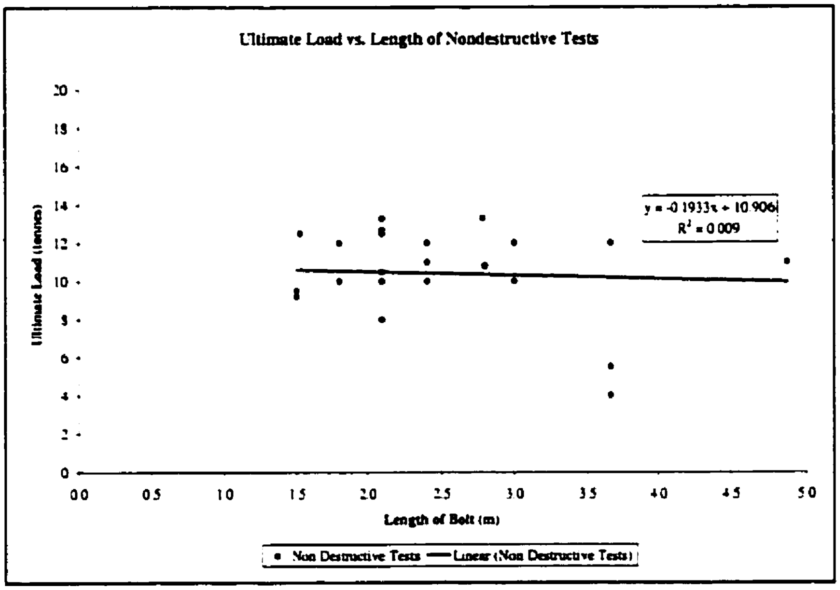

FIGURE 2-17: LENGTH VS. ULTIMATE LOAD FOR NONDESTRUCTIVE TESTS

The results of the broken and nondestructive tests show that the length of the bolt has little influence on the ultimate load for these test types, as would be expected. The correlation coefficients are very low and the trend line is horizontal. It is interesting to note that the y-intercept for the broken tests trend line is 12.1 tonnes, near the tensile strength of the bolt, and for the nondestructive tests the y-intercept is 10.9 tonnes, near the standard stopping point for a nondestructive test. This lack of influence of the length on the results of broken and nondestructive tests is reflected in the all-tests graph. The slipped-tests graph shows a small correlation coefficient of $R^2 = 0.1224$. The slope of the trend line indicates that every metre length of bolt results in a gain of 1.5 tonnes of ultimate load. This is expected because an increase in length generally involves an increase in inflated length, which results in an increased anchorage capacity. There is a large degree of scatter in the data, which is the result of various parameters (other than the length of the bolt) that influence the ultimate pullout strength of the bolt. The influence of these other parameters will be investigated in the following sections.

There is a minimum anchoring length required to fully develop the 10 tonnes of capacity for the Swellex bolt. From the data collected for effective length, in which short anchor pull tests were conducted, this minimum development length appears to be approximately 1 metre. However, there is a length beyond which there is no gain in capacity as the bolt will break long before this additional capacity is mobilized.

Once the minimum development length has been taken into consideration, the length of the bolt should be designed based on the expected depth of the damage in the rock being supported. There should be a sufficient amount of anchor length both within the damaged zone, and embedded into the rock beyond the damage zone for the bolt to be used effectively. If there is not enough anchored length (< 1m) in the damaged zone, the bolt may break at the faceplate or at intersection of the damaged zone and the undamaged rock. If there is insufficient anchorage length (< 1m) embedded on the rock beyond the damaged zone, the bolt may be pulled out as this is the effective anchoring length of the bolt.

2.8 PARAMETERS ASSOCIATED WITH INSTALLATION

Installation of the Swellex bolt is a straightforward process. A borehole is drilled and the Swellex bolt is inserted into the hole. An automatic pump is used to inject high-pressure water into the Swellex tube. The high internal water pressure inflates the tube, causing the rock mass surrounding the bolt to deform elastically. The pump is stopped and the water pressure is released. The rock mass surrounding the bolt contracts around the bolt which results in a mechanical locking effect. During the expansion process, when the Swellex bolt compresses the rock surrounding the bolt, the bolt changes shape to fit the shape of the hole. The combination of frictional and mechanical interlock is generated throughout the bolt, reinforcing the rock and increasing the ultimate bearing capacity of the bolt.[11]

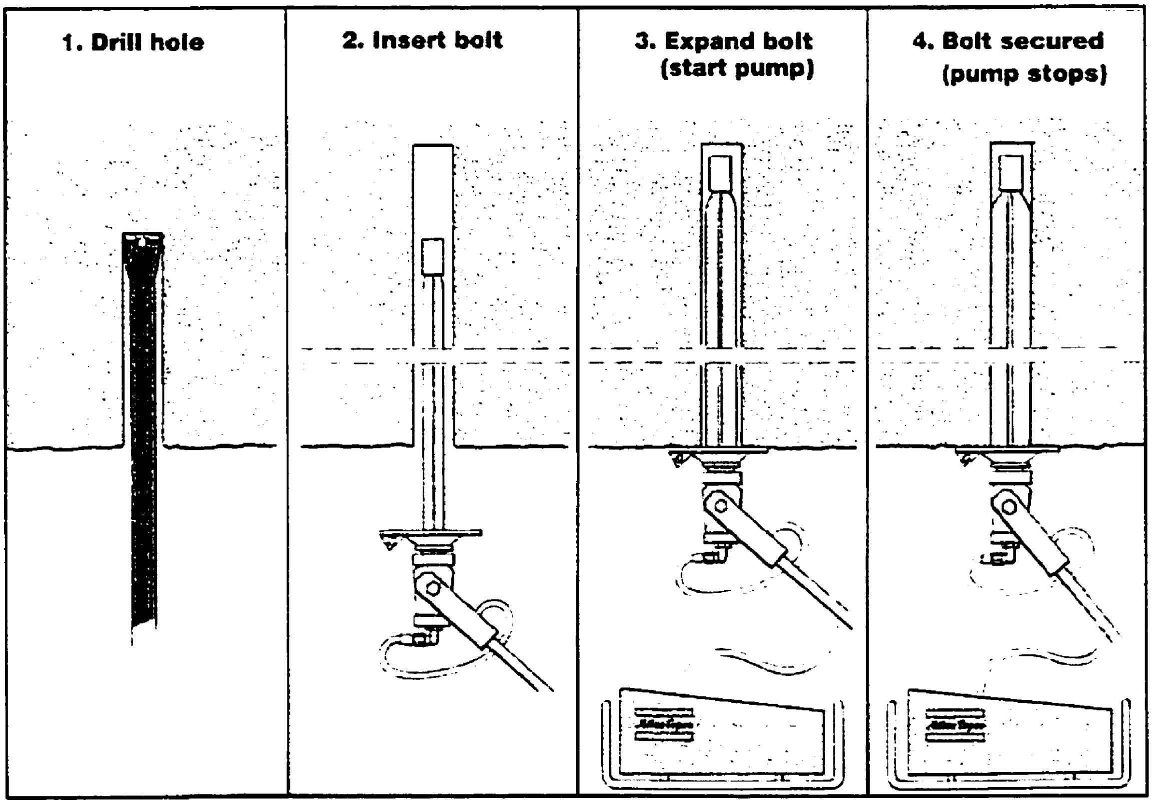

FIGURE 2-18: SWELLEX BOLT INSTALLATION PROCESS (ATLAS COPCO LTD.)[12]

There are a number of factors in the installation process which may have an influence on the performance of the Swellex bolt: drilled hole diameter, drill bit diameter, pump pressure and inflation

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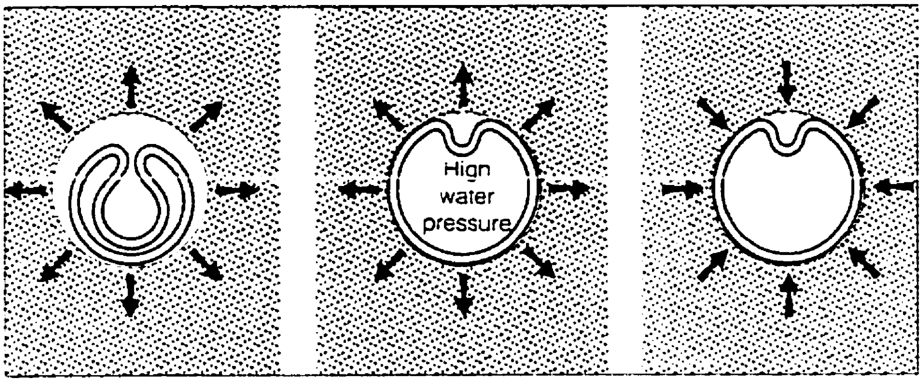
[11] Atlas Copco Ltd.

[12] Ibid.

time. Together, these factors determine the overall quality of the bolt installation, which most certainly influences the ability of the bolt to maintain a load.



Interactions between rock and Swellex rock bolt during installation. (a): Swellex bolt is placed in the hole. (b): High internal water pressure inflates the tube, causing a small elastic expansion of the borehole diameter. (c): Water pressure is released and the surrounding rock contracts thereby providing the Swellex locking effect.

Figure 2-19: Cross-sectional view of the radial and axial Anchorage development[13]

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[13] Atlas Copco Ltd.

2.8.1 Drilled Hole Diameter

According to Atlas Copco Ltd., the manufacturers and distributors of Swellex bolts, one of the primary factors that affects the quality of installation of the Swellex bolt is the drilled hole diameter. Atlas Copco recommends a drilled hole diameter in the range of 32 mm to 39 mm for their standard bolt, with the optimal hole diameter between 35 mm and 38 mm. There were 183 tests where the drilled hole diameter was recorded in the pull test data (67% of all tests). A mean and standard deviation was calculated for each test type and for all of the test types together. The results are shown in Table 2-12.

TABLE 2-12: SUMMARY STATISTICS FOR DRILLED HOLE DIAMETER FOR ALL TEST TYPES

	All Tests		Slipped Tests		Nondestructive Tests		Broken Tests	
	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)
No. of Tests	183		129		25		29	
Mean	11.33	6.45	10.74	5.81	11.98	6.49	12.59	6.93
Standard Deviation	4.16	4.27	4.54	2.92	2.85	3.99	1.61	2.22

The slipped tests have a large standard deviation for both the ultimate load and the pullout resistance, which is also reflected in the standard deviations for the all-tests dataset. The inference is that a significant number of the bolts tested were not sustaining the manufacturer's suggested minimum load of 10 tonnes. Additionally, the broken-tests mean and standard deviation of the ultimate load show that the bolt was breaking below the recommended load of 10 tonnes as well.

There were a total of 129 slipped tests of the 183 tests in which the drilled hole diameter was recorded. The slipped tests were further segmented into drilled hole diameter ranges, as determined by the manufacturer's recommended ranges. The means and standard deviations of these ranges were calculated and are shown in Table 2-13.

The manufacturer's recommendations are reflected in the statistical analysis of the different diameter ranges. The optimal range for the drilled hole diameter is, in practice, 35 to 38 mm as is reflected in the mean ultimate load of 11.99 tonnes achieved in that range with a standard deviation of 6.05 tonnes. The mean resistance for that same range is 6.57 tonnes/m with a standard deviation of 3.81 tonnes/m. The next highest ultimate load is the 32 to 34 mm range, which is still within the manufacturer's recommended drilled hole diameters, followed by the over 39 mm range, then by the under 32 mm range. The under 32 mm range, however, does not contain a sufficient amount of data to make a meaningful comparison of results.

Table 2-13: Summary Statistics for Drilled Hole Diameter for Slipped Tests

	BELOW RECOMMENDED RANGE (<32 mm)		**MANUFACTURER'S RECOMMENDED RANGE (32 mm to 39 mm)**				**ABOVE RECOMMENDED RANGE (>39 mm)**	
	28 mm		32-34 mm		35-38 mm Optimal Range		41 mm	
	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)
No. of Tests	2		65		50		11	
Mean	6.75	4.44	10.45	5.39	11.99	6.57	7.68	5.42
Standard Deviation	2.05	1.35	2.91	1.72	6.05	3.81	3.58	3.64

A graph of ultimate load vs. drilled hole diameter was plotted for ultimate load for all of the three different test types. The results are presented in Figure 2-18. The same was done for pullout resistance for all of the three different test types and the results are presented in Figure 2-19. Figure 2-20 and Figure 2-21 are graphs of the slipped tests alone for ultimate load vs. drilled hole diameter and for pullout resistance vs. drilled hole diameter, respectively. Second order polynomial trend lines were fitted through the data points using least squares regression techniques. The correlation coefficient R^2, is also shown for each of the trend lines.

In Figure 2-18 for the broken tests, the second order polynomial trend line indicates that the ultimate loads for the drilled hole diameter in the recommended range of 32 mm to 39 mm are lower than that outside of the optimal range. The pullout resistance graph indicates the opposite; that holes drilled within the optimal range improve the strength of the bolt. It is difficult to determine what influence drilled hole diameter should have on the breaking strength of the bolt. The nondestructive results are shown for interest. The trend lines in both Figures 2-18 and 2-19 indicate a low correlation value, which is correct because the ultimate load and pullout resistance are primarily a function of the tester. The slipped test results are shown separately, for greater clarity in Figure 2-20 and Figure 2-21.

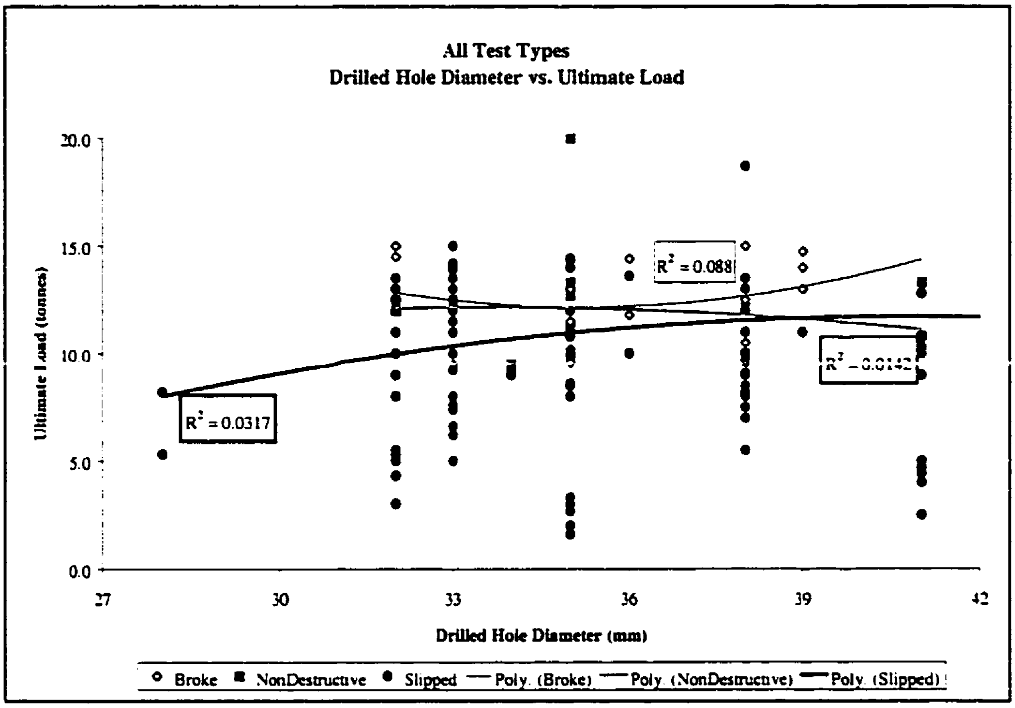

FIGURE 2-18: DRILLED HOLE DIAMETER VS. ULTIMATE LOAD FOR ALL TEST TYPES

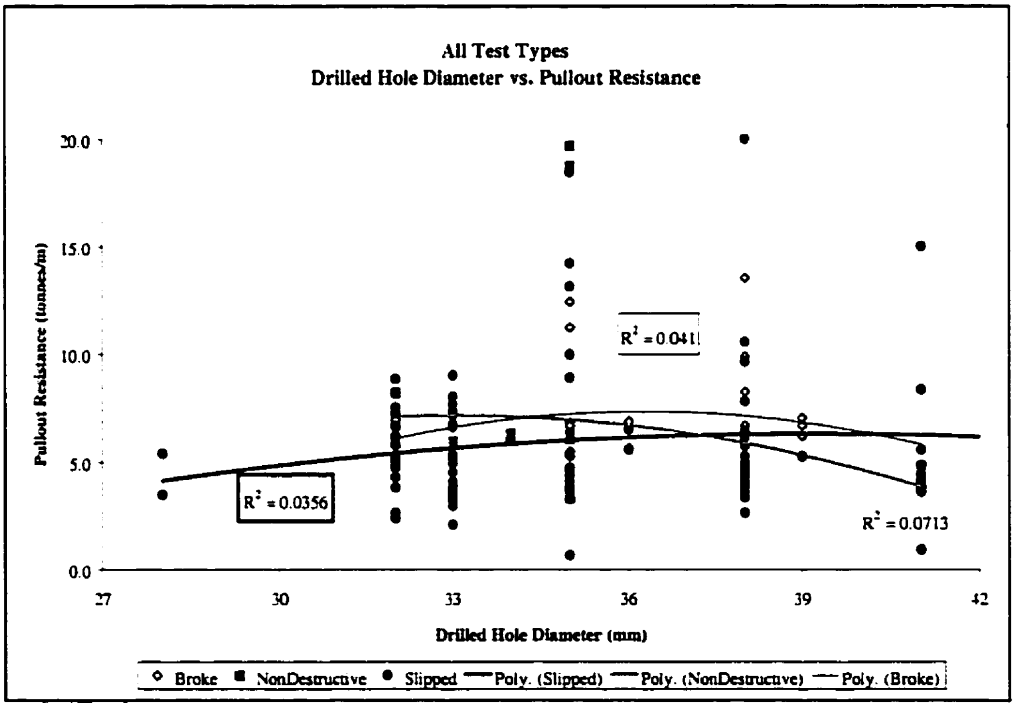

FIGURE 2-19: DRILLED HOLE DIAMETER VS. PULLOUT RESISTANCE FOR ALL TEST TYPES

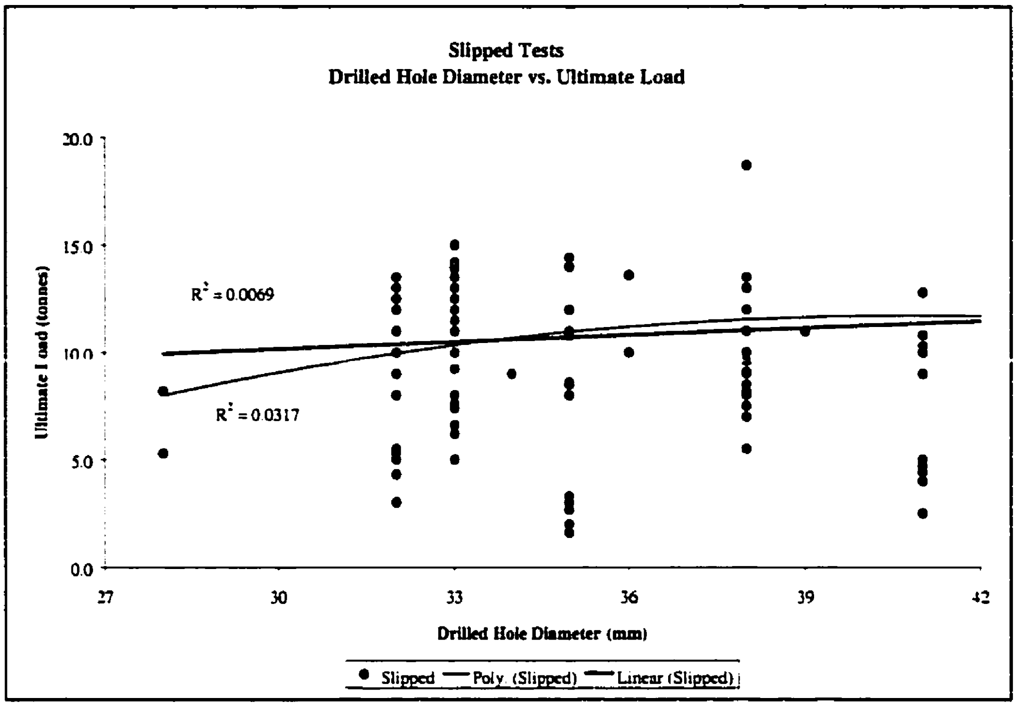

FIGURE 2-20: DRILLED HOLE DIAMETER VS. ULTIMATE LOAD FOR SLIPPED TESTS

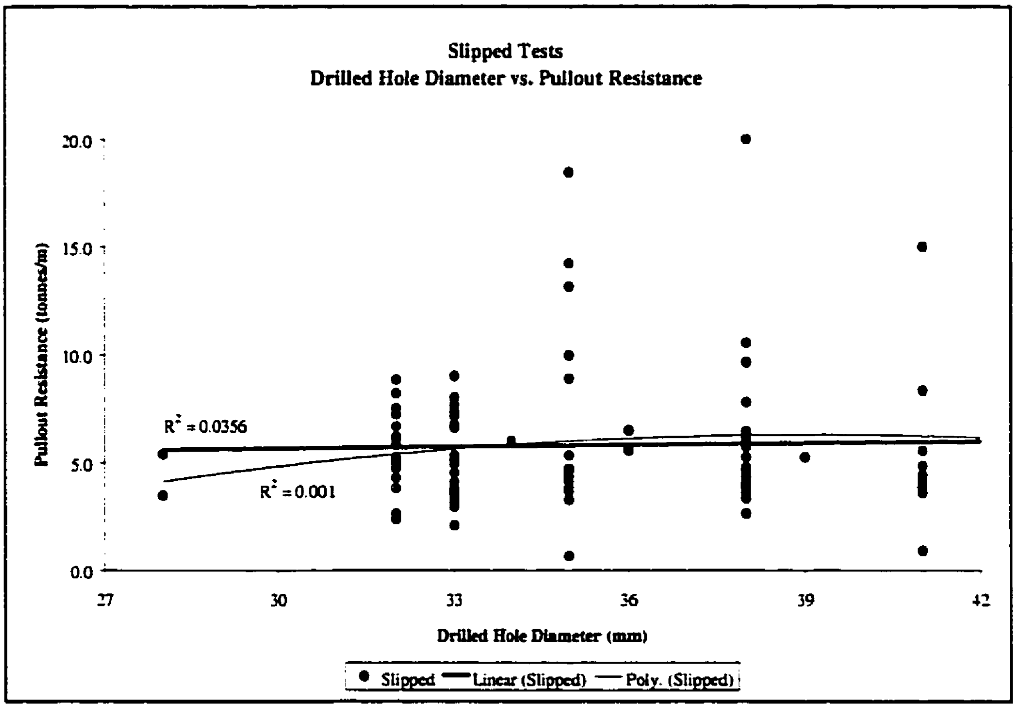

FIGURE 2-21: DRILLED HOLE DIAMETER VS. PULLOUT RESISTANCE FOR SLIPPED TESTS

The trend line in Figure 2-20 indicates that the ultimate load increases in the recommended range of 32 to 39 mm drilled hole diameter, particularly in the optimal range of 35 to 38 mm, with a peak at 38 mm. The ultimate load drops off outside the recommended range, below 32 mm and above 39 mm. The same trend line appears in the pullout resistance chart for slipped tests (Figure 2-21). The R^2 values are low, because of the large amount of scatter within the discrete intervals. In order to eliminate this scatter, the mean of each of the ranges in Table 2-13 was plotted and a trend line was fitted through the data. The result is shown in Figure 2-22.

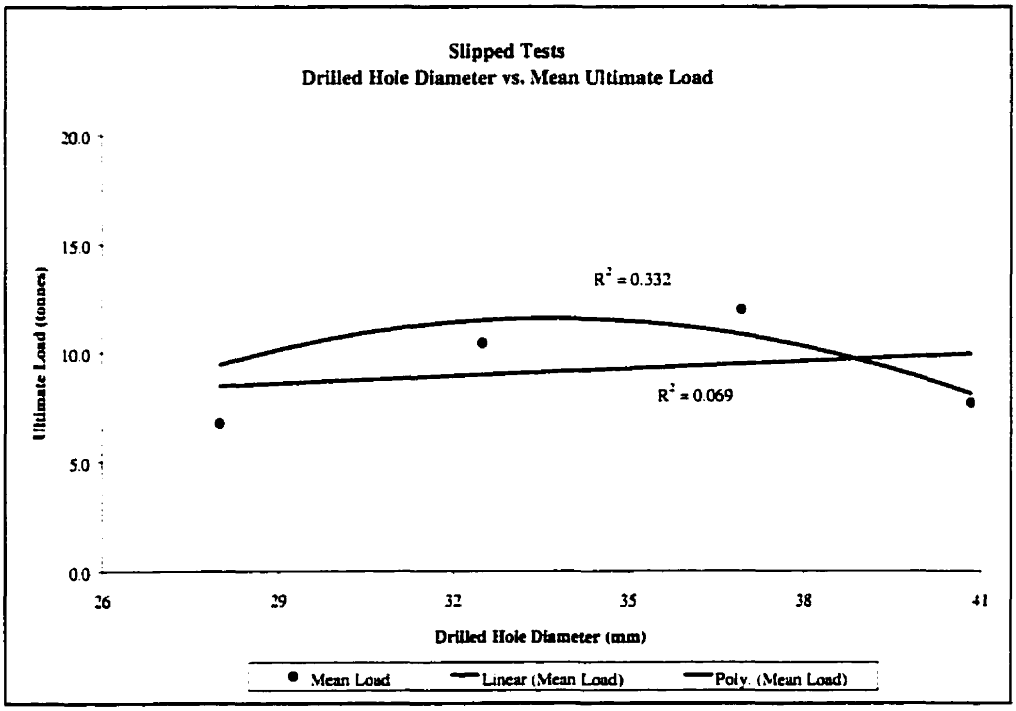

FIGURE 2-22: MEAN OF DRILLED HOLE DIAMETER RANGES (FROM TABLE 2-13) AND ULTIMATE LOAD FOR SLIPPED TESTS

The R^2 value shows a stronger correlation. A comparison between the R^2 value of 0.069 for the linear trend line and the R^2 value for the second order polynomial trend line, confirm that the relationship is non-linear. The pull test results were further broken down into the specific drilled hole diameters. The statistical results were calculated for each of the diameters for the ultimate load pull test results. The statistical results are shown in Table 2-14. The 34 mm, 37 mm and 39 mm drilled hole diameters contained only one record each, therefore the results for those diameters were not included in the table.

TABLE 2-14: SUMMARY STATISTICS FOR DRILLED HOLE DIAMETER FOR SLIPPED TESTS

	28 mm	32 mm	33 mm	35 mm	36 mm	38 mm	41 mm
	Load (tonnes)	Load (tonnes)	Load (tonnes)	Load (tonnes)	Load (tonnes)	Load (tonnes)	Load (tonnes)
No. of Tests	2	20	44	16	3	31	10
Mean	6.75	9.25	11.03	8.49	12.40	13.75	7.35
Standard Deviation	2.05	3.37	2.55	4.57	2.08	6.15	3.59

The results from the statistical analysis and the trends in Figures 2-20 and 2-21 suggest that the optimal range for the drilled hole diameter for Standard Swellex is confirmed to be 32 to 39 mm, with the optimum diameter at 35 to 38 mm. The results suggest that the larger diameters within the recommended range result in a better performance than the smaller diameters in the recommended range. Indeed, the optimal value is at the larger end of the recommended range. This is a result of the anchorage mechanics of the bolt. Two factors influence the performance of the bolts as it relates to drilled hole diameter: the ability of the bolt to fully inflate to generate the mechanical locking effect and the ability of the bolt to generate the axial frictional force. At the lower end of the drilled hole diameters, the bolt is not able to fully inflate, due to the smaller diameter hole. The hole is not large enough to allow the folded portion of the bolt to unfold, which inhibits the spring-like action of the folded portion from opening. In the larger diameter holes, the bolt's fully inflated diameter (41 mm) is close to the diameter of the hole, and the surrounding material undergoes little elastic deformation, and resultantly, little compression back on to the bolt takes place once the water pressure is released. In the larger diameter hole, the bolt does not fully conform to the irregularities of the borehole and less axial friction is developed.

Conclusions

The most important result of this analysis is that the operator should realise that it is crucial to remain inside the optimal range, as the ultimate load significantly decreases outside of this range. This is one of the most important factors effecting the performance of Swellex bolts. Often, the correct size drill bit diameter is not available and the installer substitutes another size. The results of the analysis indicate that this would be a mistake. Every effort should be made to obtain the correct size drill bit and to drill a hole in the optimal range in order to achieve maximum performance from the Swellex bolt.

2.8.2 Drill Bit Diameter

As noted in the previous section (2.8.1 Drilled Hole Diameter), one of the primary factors that affects the quality of installation of the Swellex bolt is the drilled hole diameter. Atlas Copco Ltd. recommends a drilled hole diameter in the range of 32 mm to 39 mm for their standard bolt, with the optimal hole diameter between 35 mm and 38 mm. Since a typical drill bit drills a hole that is 3 mm larger than the bit size, the recommended range of bit sizes for the recommended hole is 29 to 36 mm, with an optimum range of bit size between 32 to 35 mm. It is important to note that in some cases, the drill bit diameter will not always result in a hole that is 3 mm larger than the bit size. In soft ground, over-breaking during drilling may occur, and will result in larger diameter hole. In hard ground, the opposite will occur. There were a total of 51 tests where the drill bit diameter was recorded in the pull test data (19% of the total tests). A mean and standard deviation was calculated for each of the test types and all of the test types together. The results are shown in Table 2-15.

TABLE 2-15: SUMMARY STATISTICS FOR DRILL BIT DIAMETER FOR ALL TEST TYPES

	All Tests		Slipped Tests		Nondestructive Tests		Broken Tests	
	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)
No. of Tests	51		23		18		10	
Mean	10.95	5.14	9.91	4.68	11.08	5.17	13.11	6.18
Standard Deviation	2.36	1.22	2.74	1.37	1.33	0.88	1.10	0.69

Broken and Nondestructive Tests

The pull tests results were plotted for ultimate load and for pullout resistance for all of the three different test types, and for the slipped tests alone. The results are shown in Figure 2-23 and Figure 2-24. In Figure 2-23 (ultimate load) for the broken tests, the trend line is almost horizontal. The pullout resistance trend line (Figure 2-24) for broken tests indicates that the optimal range for drill bit diameters recommended by the manufacturer (32 mm to 35 mm) improves the strength of the bolt. This latter trend line has a relatively high correlation value of $R^2 = 0.4382$. Like the drilled hole diameter, it is difficult to determine what influence the drill bit diameter should have on the breaking capacity of the bolt. More data is required to rule this parameter out.

Slipped Tests

From Table 2-15, the slipped tests have a large standard deviation for both the ultimate load and the pullout resistance, which is also reflected in the standard deviations for all of the test types together. In addition, the mean ultimate load is rather low, at 9.91 tonnes with a standard deviation of 2.74

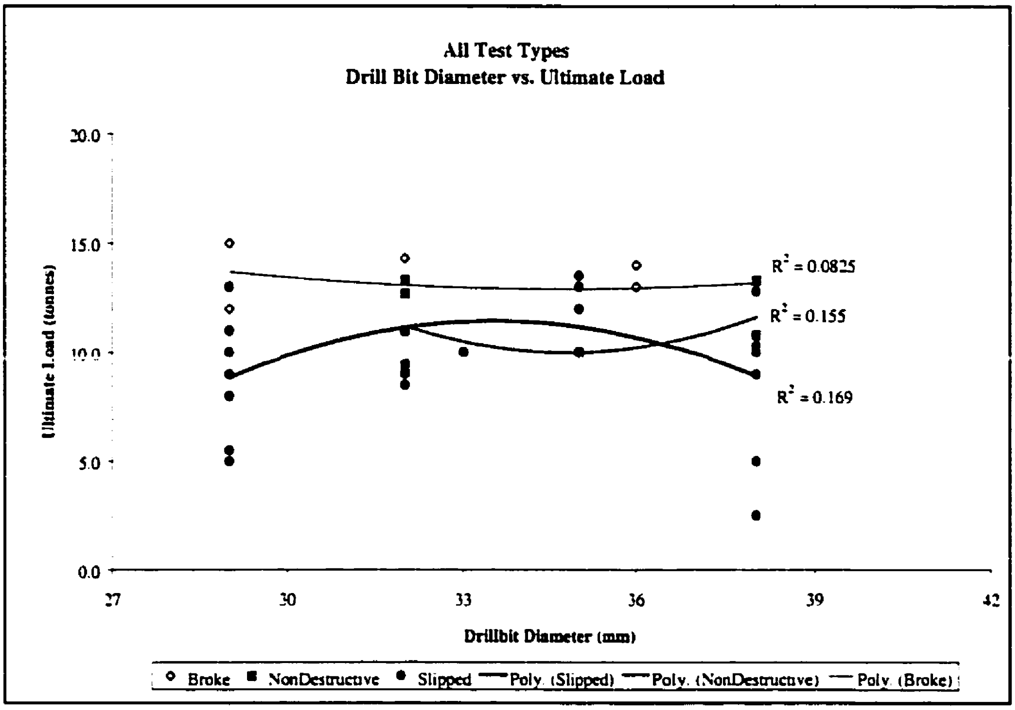

FIGURE 2-23: DRILL BIT DIAMETER VS. ULTIMATE LOAD FOR ALL TEST TYPES

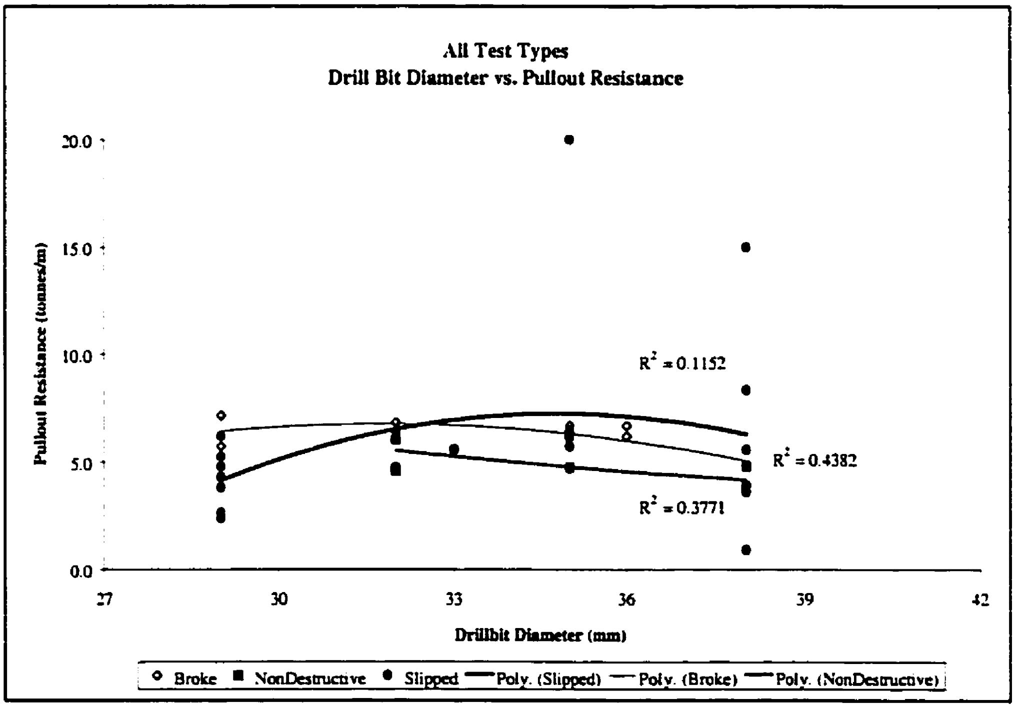

FIGURE 2-24: DRILL BIT DIAMETER VS. PULLOUT RESISTANCE FOR ALL TEST TYPES

tonnes. The inference is that a significant number of the bolts tested were not sustaining the manufacturer's suggested minimum load of 10 tonnes. The slipped tests were further segmented into drill bit diameter ranges, as determined by the manufacturers recommended ranges. The means and standard deviations of these ranges were calculated and are shown in Table 2-16.

TABLE 2-16: SUMMARY STATISTICS FOR DRILL BIT DIAMETER FOR SLIPPED TESTS

	MANUFACTURER'S RECOMMENDED RANGE						**ABOVE RECOMMENDED RANGE**	
	29 mm		32 mm		35 mm		38 mm	
			Optimal Range					
	Load	Resistance	Load	Resistance	Load	Resistance	Load	Resistance
No. of Tests	9		4		5		5	
Mean	9.06	4.31	9.63	5.22	12.30	5.50	9.28	3.75
Standard Deviation	2.60	1.24	1.11	0.68	1.79	0.74	3.94	1.77

The manufacturer's recommendations are confirmed by the statistical analysis of the different diameter ranges. The optimal range for drill bit diameter is, in practice, 32 to 35 mm as is reflected in the maximum mean ultimate load of 12.30 tonnes achieved in that range with a standard deviation of 1.79 tonnes. The mean resistance for that same range is 5.50 tonnes/m with a standard deviation of 0.74 tonnes/m. The next highest ultimate load is the 32 mm range, which is still within the manufacturer's optimal drill bit diameters, followed by the 29 mm range, which is also within the manufacturer's recommended range of diameters, followed by the over 38 mm range which is outside the manufacturer's recommended range. The pullout resistance results follow the same pattern. However, it should be noted that this subset (slipped tests with drill bit diameter information) of the pull test records contains very little data and it is difficult to obtain reliable trends and statistics from such a small sample. Clearly, more data is required in this area to obtain reliable results and to confirm the results of this aspect of the study.

The trend line in Figure 2-25 indicates that the ultimate load increases in the recommended range of 29 to 35 mm drilled hole diameter, particularly in the optimal range of 32 to 35 mm, with a peak at 35 mm. The ultimate load drops off outside the recommended range, below 29 mm and above 38 mm. The same trend line appears in the pullout resistance chart for slipped tests, Figure 2-26. The R^2 values are low, because of the large amount of scatter within the discrete intervals. In order to eliminate this scatter, the mean of the ranges in Table 2-16 were plotted and a trend line was fitted through the data. The result is shown in Figure 2-27.

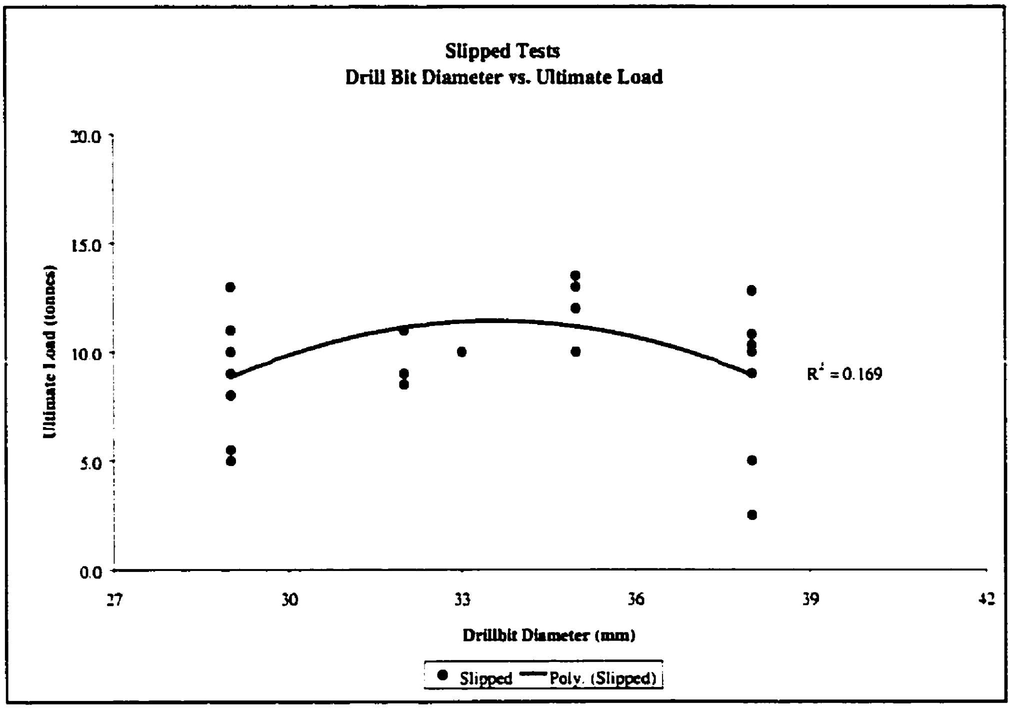

FIGURE 2-25: DRILL BIT DIAMETER VS. ULTIMATE LOAD FOR SLIPPED TESTS

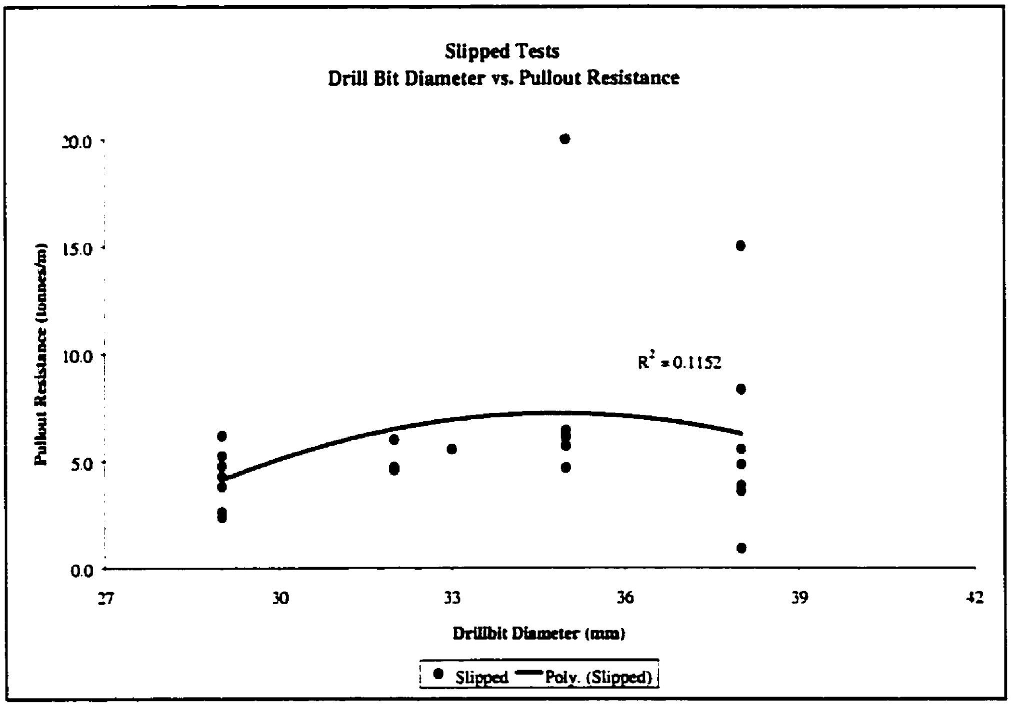

FIGURE 2-26: DRILL BIT DIAMETER VS. PULLOUT RESISTANCE FOR SLIPPED TESTS

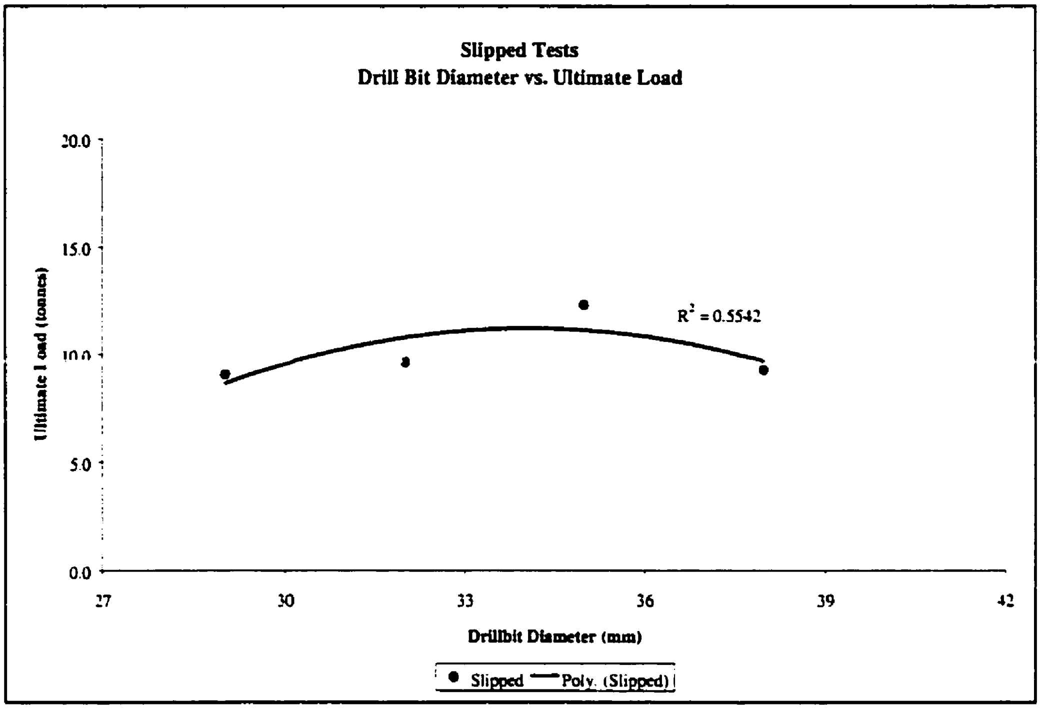

FIGURE 2-27: MEAN OF DRILL BIT DIAMETERS (FROM TABLE 2-15) VS. ULTIMATE LOAD FOR SLIPPED TESTS

The R^2 value shows a stronger correlation of 0.5542. The results from the statistical analysis and the trends apparent on the chart in Figures 2-25 and 2-26 suggest that the optimal range for the drill bit diameter for Standard Swellex is indeed 29 to 35 mm, with an optimum diameter of 32 to 35 mm.

Conclusions

As with the drilled hole diameter, the results suggest that the larger diameters within the recommended range result in a better performance than the smaller diameters in the recommended range. The recommendations for this parameter are essentially the same as for the drilled hole diameter (see Section 2.8.1). It is important to note that in some cases, the drill bit diameter will not always result in a hole that is 3 mm larger than the bit size. In soft ground, over-breaking during drilling may occur, and will result in a larger diameter hole. In hard ground, the opposite will occur. The trends observed in the drill bit size parameter are the result of the underlying influence of the drilled hole diameter which is the more important of the 2 parameters. Therefore, it is essential to select a drill bit size that will result in the appropriate size of hole given the ground conditions.

2.8.3 Pump Pressure

Swellex bolts are made of a circular steel tube that has been folded to reduce its diameter. The bolts are inserted into a drilled hole 32-39 mm in diameter. High pressure water is then pumped into the bolt and used to inflate the bolt within the hole, creating the mechanical lock and axial friction throughout the bolt length. The level of water pressure, which is called the pump pressure, is one of the primary factors that effects the quality of installation of the Swellex bolt. The pump pressure is also a check of the quality of installation. When the pump reaches a pre-set pressure of 30 MPa, the quality of bolt and installation is verified, according to Atlas Copco Ltd.[14] In their product manual, Atlas Copco Ltd. recommends a pump pressure of 30 MPa for their standard bolt.[15]

Pump pressure information was recorded in 97 of the pull test records (36% of all pull test records). The majority of the test records were for bolts that had been installed with the recommended 30 MPa. It is uncertain whether this information reflects the actual pump pressure at which the bolts were installed, or whether it reflects the "desired pressure" that was entered in by the tester at the time of testing because it is the recommended pressure. Typically, the time of testing is well after the time of installation (see Section 2.9.2). If the pump pressure is not recorded at the time of installation or it is not accurately referenced at the time of testing, the recorded pump pressure information may be incorrect. However, it is difficult to determine which of the available data is reliable and which is not.

The majority of the data is lumped around 30 MPa. This means that there is a large amount of scatter with respect to the ultimate load and pullout resistance at the recommended value of pump pressure. This does not necessarily mean that the pump pressure has little influence on the pull test results. Indeed it does. In many of the pull test records where the bolt performed poorly, the comments of the tester noted that the bolt was not properly inflated. The range of load and resistance values at 30 MPa, may be attributed to other underlying influences within that range of data, such as drilled hole diameter, corrosion or other factors which were also found to have some influence on the performance of the bolt.

The pull test information was grouped by test type: slipped, broken and nondestructive tests. The mean and standard deviation were calculated for all of the test types grouped together as a set and for each test type individually. The results are presented in Table 2-17.

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[14] Atlas Copco Ltd.

[15] Ibid.

TABLE 2-17: SUMMARY STATISTICS FOR PUMP PRESSURE FOR ALL TEST TYPES

	All Tests		Slipped Tests		Nondestructive Tests		Broken Tests	
	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)
No. of Tests	97		68		6		23	
Mean	11.21	6.53	10.40	6.01	14.73	9.86	12.69	7.21
Standard Deviation	5.22	3.63	5.83	3.83	1.33	7.42	1.62	2.37

The large standard deviation in the slipped tests reflects the large range of load and resistance values around 30 MPa. A large number of the slipped tests are not holding the minimum suggested 10 tonnes of load. Since only 6 of the 97 tests were nondestructive, the results from the nondestructive data must be viewed carefully. There were a number broken tests, about 25% of the total. The mean ultimate load sustained in the broken tests before the bolt broke was 12.69 tonnes with a standard deviation of 1.62 tonnes. This is approximately, the ultimate tensile strength of the steel before expansion of 11 tonnes.[16] This suggests that the bolts in the broken tests subset of data are performing at about the expected level with respect to the breaking strength of the steel. The bolt is breaking at the manufacturer's minimum suggested breaking load.

The ultimate load and the pullout resistance results were plotted against the pump pressure for each of the test types. Linear regression techniques were used to fit a linear trend line through the data. The associated correlation coefficients, R^2, were calculated and are shown on the graphs as well. The results are presented in Figures 2-28 and 2-29.

Broken and Nondestructive Tests

The broken test trend line has a very low correlation value both in the ultimate load chart (Figure 2-28) and in the pullout resistance chart (Figure 2-29), of $R^2 = 0.0001$ and $R^2 = 0.0133$, respectively. This is due in part to the clustering of data around 30 MPa (19 of the 23 broken tests). However, it is also attributable to the lack of influence that pump pressure has on the breaking strength of the bolt.

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[16] Stillborg.

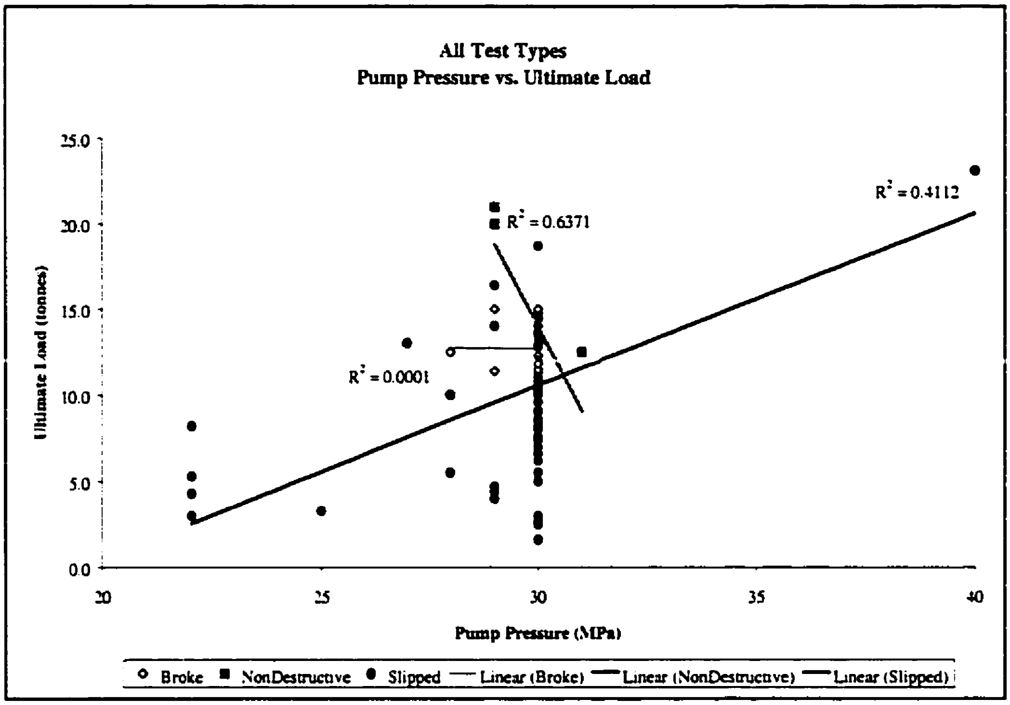

FIGURE 2-28: PUMP PRESSURE VS. ULTIMATE LOAD FOR ALL TEST TYPES

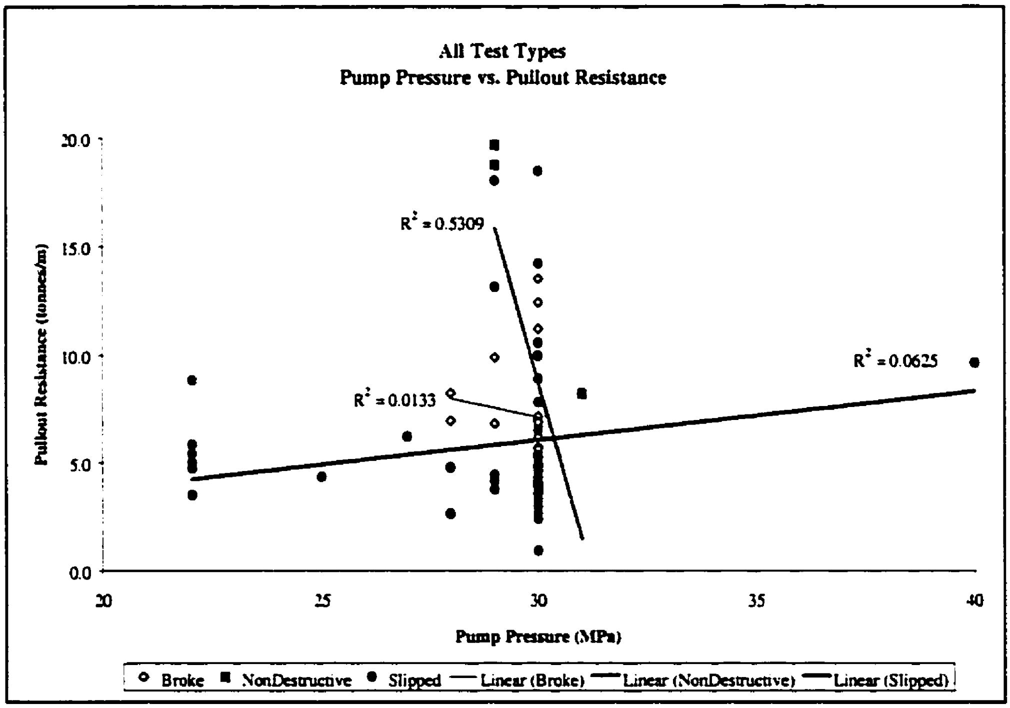

FIGURE 2-29: PUMP PRESSURE VS. PULLOUT RESISTANCE FOR ALL TEST TYPES

In any case, the results show that pump pressure has little influence on the performance of the bolts that broke. Only 1 of the 23 tests that broke, broke before the minimum suggested tensile strength of the bolt at 10 tonnes.

The trend line for the nondestructive tests is shown for interest. The results of a nondestructive test are overwhelmingly influenced by the tester. The nondestructive tests results do provide a minimum value that those bolts are maintaining, and none of the 6 were stopped before the minimum 10 tonnes, which means that the nondestructive tests in this subset are performing well.

Slipped Tests

The results of the slipped tests are shown alone for clarity in Figures 2-30 and 2-31.

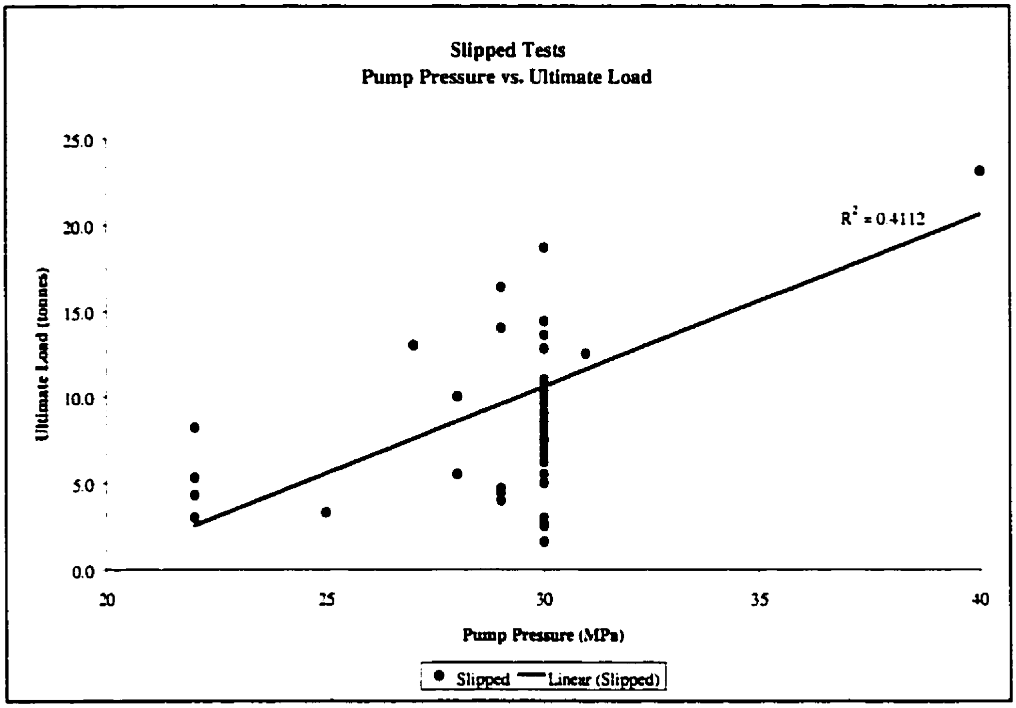

FIGURE 2-30: PUMP PRESSURE VS. ULTIMATE LOAD FOR SLIPPED TESTS

The trend line in both the ultimate load chart, Figure 2-30, and in the pullout resistance chart, Figure 2-31, indicate that the performance of the bolt improves with increasing pump pressure. It should be noted that the symbol at 40 MPa is actually 5 data points. The correlation value of $R^2 = 0.4112$ in the ultimate load chart is extremely high compared to any of the other factors. The $R^2 = 0.0625$ is lower for the pullout resistance, however it is still significant compared to the other factors.

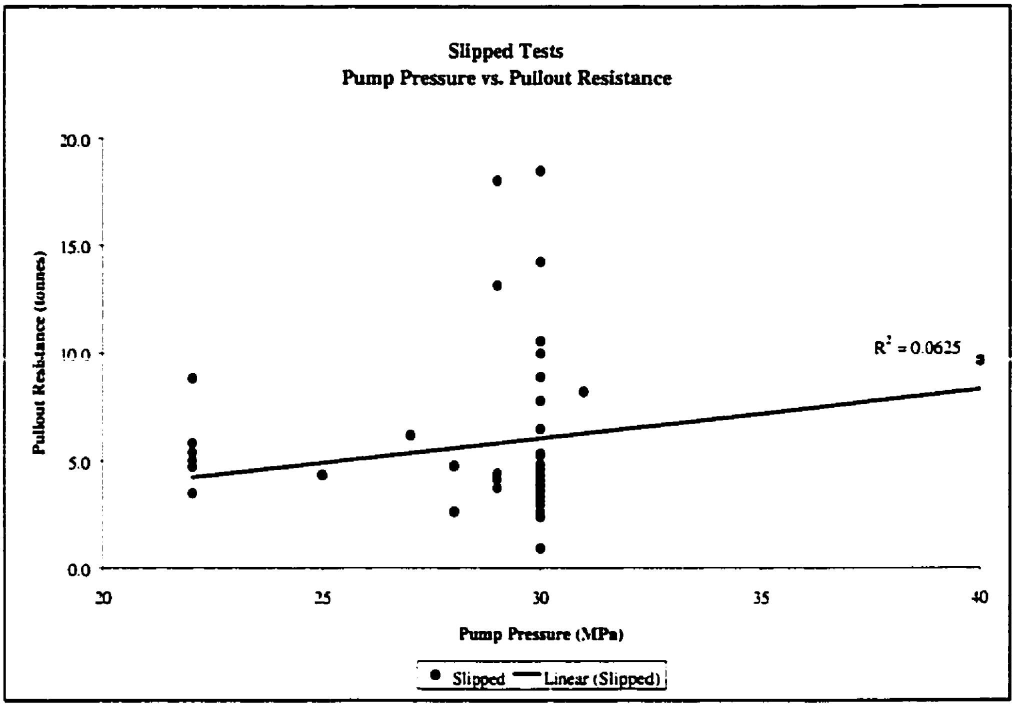

FIGURE 2-31: PUMP PRESSURE VS. PULLOUT RESISTANCE FOR SLIPPED TESTS

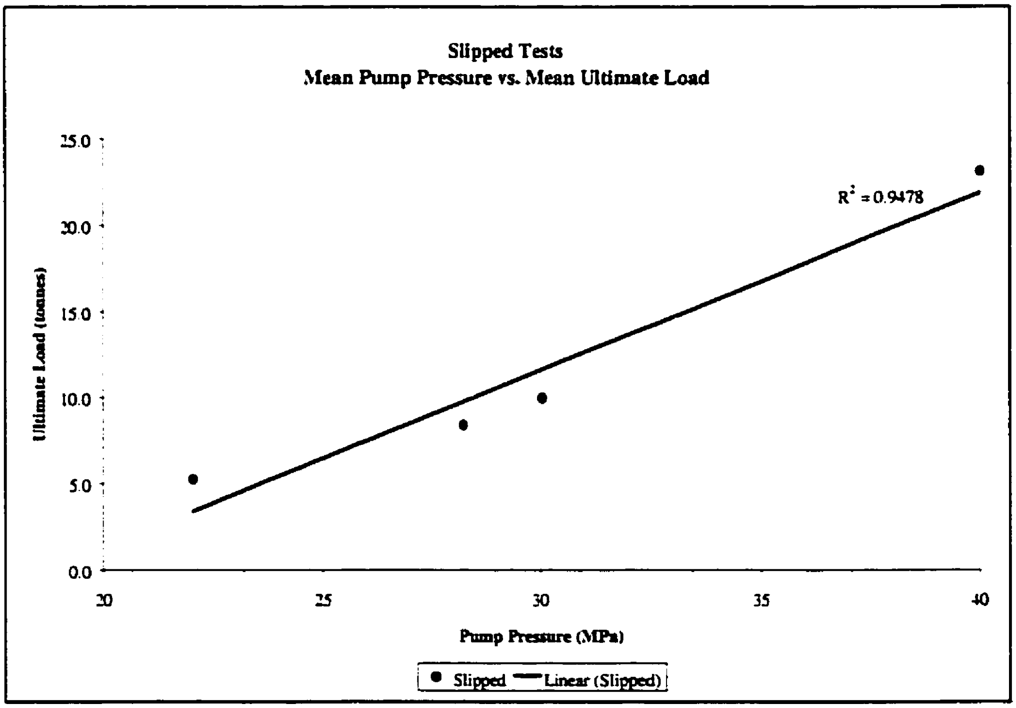

FIGURE 2-32: MEAN VALUES FOR ULTIMATE LOAD VS. PUMP PRESSURE FOR SLIPPED TESTS

Another significant observation in the ultimate load vs. pump pressure graph for slipped tests, was the behaviour of bolts which were inflated at a pump pressure of less than 27 MPa. *None* of these bolts attained the minimum suggested pullout load of 10 tonnes. Another trend is the improved performance of the bolt inflated at a pump pressure of 40 MPa. These two observations indicate that a higher pump pressure during installation is preferable to a lower pump pressure.

The mean value was calculated for the slipped test for 4 ranges of pump pressure for the ultimate load in order to eliminate some of the scatter. The ranges were 20 – 24.99 MPa, 25 – 29.99 MPa, 30 – 34.99 MPa, and 35 – 40.00 MPa. The results were plotted Figure 2-32.

The R^2 value for this chart is 0.9478, suggesting a strong correlation between the pump pressure and the performance of the bolt. The data at the 40 MPa pump pressure, was obtained from a study that was done in a mine by Atlas Copco Ltd., to help a client achieve better performance from the bolt, as they were having problems in extremely hard rock conditions. They found that increasing the pump pressure from 30 MPa to 40 MPa improved the performance of the bolt by about 25%, (the ultimate load increased from 18 tonnes to 23 tonnes). These tests were eliminated from the rest of the study (see Section 2.5.2) but were included in the analysis for pump pressure for two reasons. Even without the points the trend line indicates that an increase in pump pressure results in an increase in ultimate load. Also, these points were the only records that were available for any pump pressure appreciably higher than 30 MPa.

Conclusions

The pump pressure is extremely important to the quality of installation of the bolt, which in turn affects the ultimate load. There is a large amount of scatter around the 30 MPa pump pressure, mostly likely for two reasons. The first is that some of the data recorded as having a pump pressure of 30 MPa may not actually be 30 MPa but was recorded as such because it is the recommended pump pressure. The other reason for the scatter is the influence of other underlying factors. The influence appears in the other charts as well, particularly in factors which involve discrete intervals such as the drill hole diameter. More data is required, and accurate recording of the pump pressure is required at the time of installation, in order to obtain reliable results and verify these trends. However, from the data available, it clear that a minimum of 30 MPa is required and if possible, additional pressure does help the quality of installation significantly and increase the ultimate load of the bolt as well.

2.8.4 Inflation Time

This parameter was rarely recorded as a part of the pull test information. This lack of information may be attributed to the fact that many of the bolts are pull tested long after the have been installed and the inflation time information had not been recorded at the time of installation or the information was no longer available. Even in tests where the bolt was installed on the same date as the pull test, inflation time was not recorded. In many of the tests where the ultimate load of the bolt was extremely low, the comments of the tester were that the bolt was not fully inflated. The inflation time along with the pump pressure are the two factors which would determine the quality of installation, particularly the full inflation of the bolt. If the high pressure water is not injected for a sufficient amount of time, then the bolt will not properly inflate. This parameter should be systematically recorded in the future to fully investigate the effect and correlation of inflation time with the capacity of the bolt.

2.9 PARAMETERS ASSOCIATED WITH TIME

Currently, Swellex is primarily used as a means of temporary support in many underground operations. The standard time frame is anywhere from six months to a year. In some cases, such as in low corrosive environments, the bolt can be used for up to 10 years. The reason for the use of the bolt for temporary support is due in part to the low cost and ease of installation. It is also due in part to the tendency of the bolt to under-perform with time. Corrosion and the age of the bolt are two factors that are associated with time. The installation date and the test date are also associated with time. The latter two factors were used to determine the age of the bolt, as this information was not always provided. Statistical analysis and charts were plotted for each of these parameters against the ultimate load and the pullout resistance of the bolt. The results are presented in the following sections.

2.9.1 Corrosion Level

Corrosion information was recorded for 65 pull tests results, 24% of the total number of tests. 35 of these were slipped tests, 19 were nondestructive tests and 11 were broken tests. The information recorded for the level of corrosion was all qualitative. Terms such as *very corroded*, *some rust*, *little corrosion* and *surficial corrosion* were used to indicate the level of corrosion in the bolt. For the purpose of this thesis, a standard set of terminology was developed which translated the qualitative terms that were commonly used in practice, into a ranking system. This was done in order to provided a standardized method for the comparison of pull test results. The pull test data was then interpreted and reclassified into this standard set of terminology in order to develop a viable set of data that could then be analysed statistically. The terminology used , listed in the ranked order, was:

☐ 1 = none (no corrosion present)
☐ 2 = surficial (surficial corrosion present on bolt)
☐ 3 = little corrosion (more corrosion than surficial but not full coverage of the bolt)
☐ 4 = moderate corrosion (near full coverage of the bolt with corrosion)
☐ 5 = very corroded (indicating nearly complete corrosion)

While this classification system is inherently flawed (it uses subjective terms and subjective rationale), it is sufficient to analyse the given data. The mean and standard deviation were calculated for each of the test types. The results are shown in Table 2-18. The mean and standard deviation was also calculated for the different levels of corrosion within the slipped tests subset of data. The results are shown in Table 2-19.

TABLE 2-18: SUMMARY STATISTICS FOR CORROSION LEVEL FOR ALL TEST TYPES

	All Tests		Slipped Tests		Nondestructive Tests		Broken Tests	
	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)
No.of Tests	65		35		19		11	
Mean	10.77	4.95	11.77	5.14	10.00	4.93	8.93	4.37
Standard Deviation	2.34	1.07	2.18	1.13	0.00	0.33	3.25	1.54

TABLE 2-19: SUMMARY STATISTICS FOR CORROSION LEVEL FOR SLIPPED TESTS

	Surficial Corrosion		Little Corrosion		Moderate Corrosion		Very Corroded	
	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)
No. of Tests	12		11		10		2	
Mean	10.07	5.20	12.77	4.00	12.88	6.30	10.95	5.21
Standard Deviation	1.64	0.56	1.84	0.84	2.01	0.71	1.34	0.64

A few inferences can be drawn from the statistical data. For the total of 65 tests where the corrosion level was recorded, the mean ultimate load was 10.77 tonnes with a standard deviation of 2.34 tonnes. Since the minimum load that the bolt should sustain is 10 tonnes, it is apparent from this subset of data that a significant number of tests are not sustaining the minimum load specified by the manufacturer.

Broken and Nondestructive Tests

The values on the x-axis represent the ranking system described previously in this section. A second order polynomial trend line was fitted through the data points for each of the test types. Both Figure 2-33 and Figure 2-34 show the same result for the nondestructive tests. The trend line is horizontal. This is a direct result of the way a nondestructive test is carried out. The standard deviation of 0.00 tonnes (Table 2-18) for the nondestructive tests can be expected since nondestructive tests are carried out in such a manner as to yield this result.

The results for the broken tests are the same for both the ultimate load and the pullout resistance. The second order polynomial trend line shows that the strength of the bolt decreases with an increase in the level of corrosion, for destructive tests. This result should also be expected because corrosion affects the performance of steel. The R^2 values are relatively high, with a value of 0.3225 for the ultimate load and 0.3470 for the pullout resistance. The steep slope of the trend line indicates that the strength of the bolt is highly sensitive to the level of corrosion in the bolt.

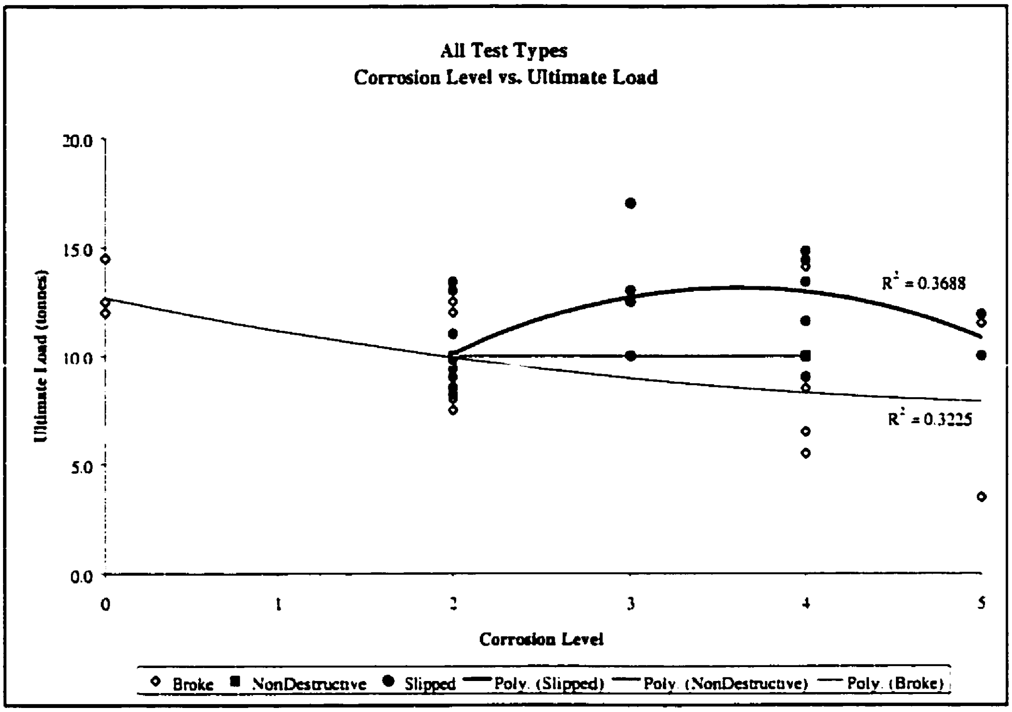

FIGURE 2-33: CORROSION LEVEL VS. ULTIMATE LOAD FOR ALL TEST TYPES

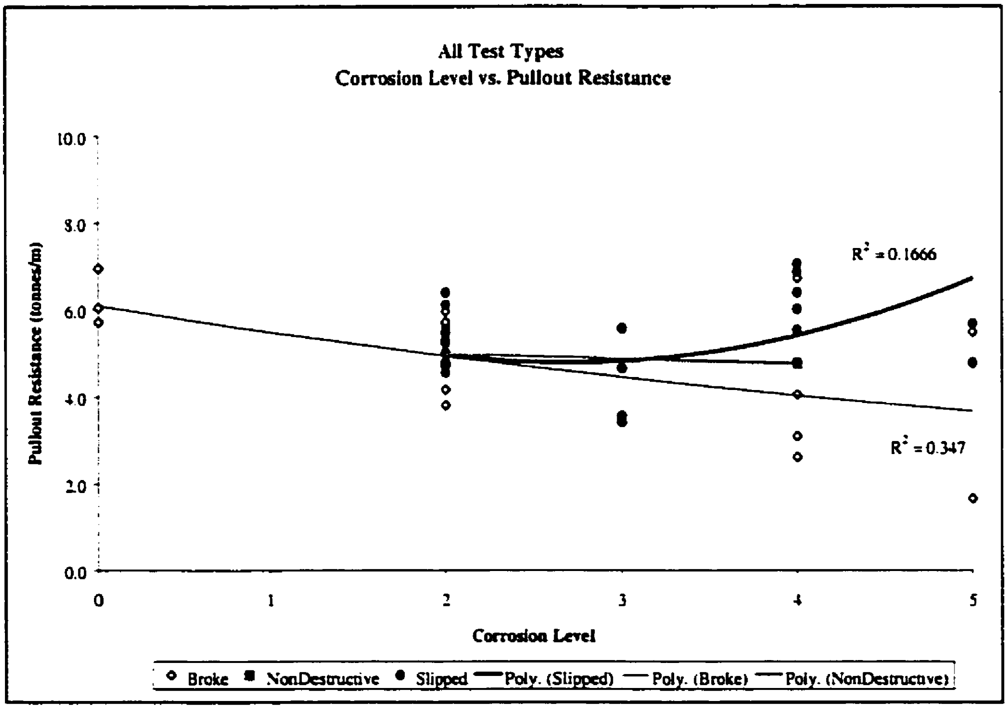

FIGURE 2-34: CORROSION LEVEL VS. PULLOUT RESISTANCE FOR ALL TEST TYPES

Slipped Tests

In order to analyse the influence of corrosion level on the slip load of the bolt, the slipped tests were analysed as a group and were also segmented by degree of corrosion and analysed within these groupings. The slipped tests held a mean ultimate load of 11.77 tonnes with a standard deviation of 2.18 tonnes for the 35 tests. Implying that, for this subset of tests, a significant number of tests (about 15-20%) of the bolts would not hold the minimum load of 10 tonnes.

When the slipped tests were further divided into subsets by their level of corrosion, certain trends were noticed. The statistical data indicates that the ultimate load and the pullout resistance for the bolt increases with the level of corrosion, up to the moderate corrosion level, then the load and resistance decrease. This result can be explained by the fact that Swellex is a frictional bolt and a moderate degree of corrosion serves to improve the friction in the bolt. Also, the development of corrosion creates a physical bond between the bolt and the hole, similar to a rusted nut and bolt. Although the dataset is relatively small in number, only 35 tests, the trend also appears in the charts and the R^2 values (correlation coefficient) are significantly higher than most of the other factors. This suggests that the degree of corrosion has a significant role in the strength of the bolt. Ultimate load and the pullout resistance were plotted against the corrosion level for all of the tests and trend lines were drawn for each test type, these two charts are shown in Figures 2-33 and Figure 2-34.

At a certain point, which, according to the data, occurs at the "*very corroded*" level of corrosion in the bolt, the strength of the bolt degrades. This degradation in strength is due to corrosion lowering the tensile strength of the bolt. The "*very corroded*" level is the point at which the two factors intersect. At the "*very corroded*" level, the ultimate load chart shows that the strength of the bolt degrades, while the pullout resistance chart shows that the strength of the bolt continues to improve. Not only is the former result the more statistically reliable result (R^2 value of 0.3688, for the ultimate load vs. the R^2 value of 0.1666 for the pullout resistance), it is also the more logical result.

The results for slipped tests alone, are shown on Figures 2-35 and 2-36. In order to verify the results in Figure 2-34 for the slipped tests, the mean values for ultimate load for slipped tests as calculated in Table 2-19 were plotted in Figure 2-37. This was done in order to eliminate the scatter which results from interpreting qualitative descriptions in order to lump them into discrete groupings such as '*little*', '*moderate*' and '*very corroded*'. In addition, Figure 2-38 shows the ultimate load for broken and slipped tests. The broken tests were included in order to observe the relationship between the corrosion level, the result of the test, (will the bolt break or will it pullout), and the pullout load of the

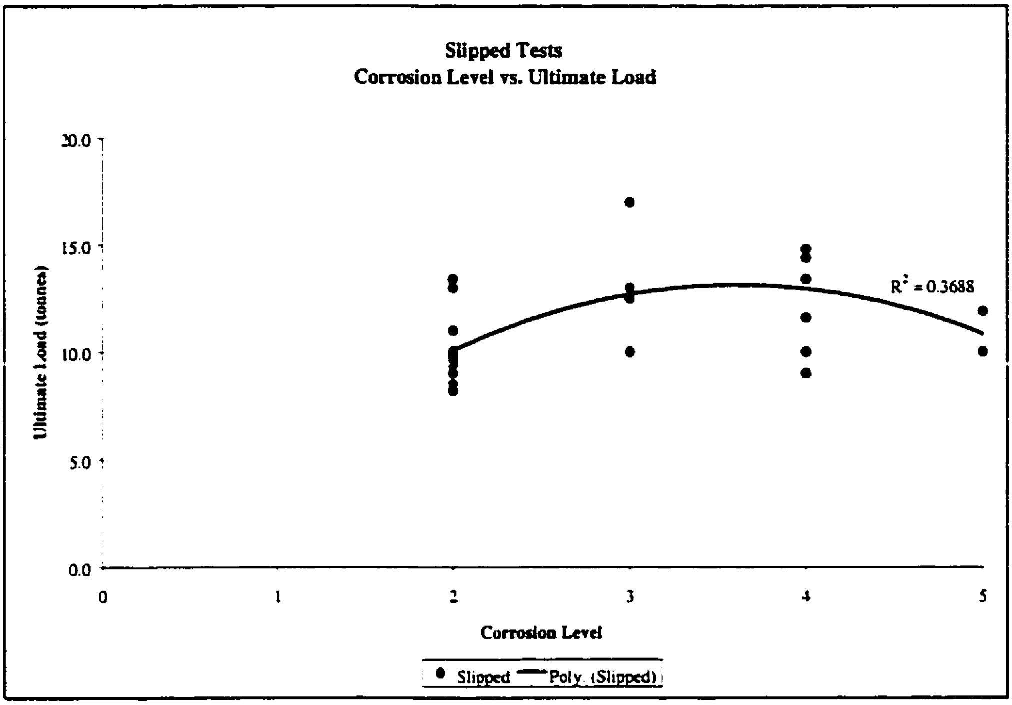

FIGURE 2-35: CORROSION LEVEL VS. ULTIMATE LOAD FOR SLIPPED TESTS

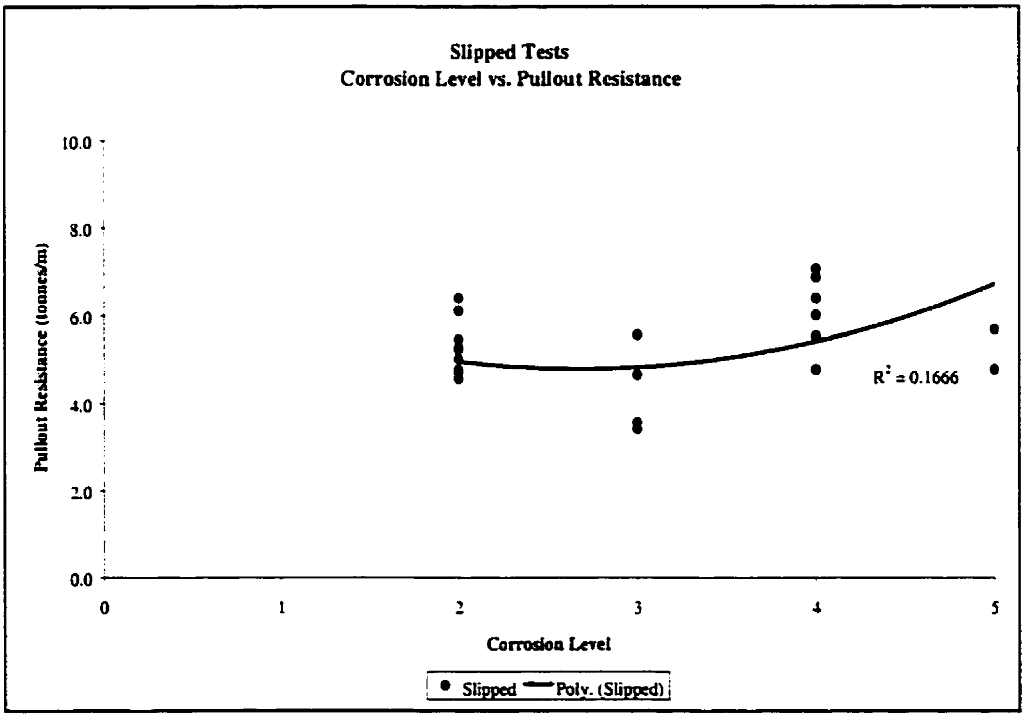

FIGURE 2-36: CORROSION LEVEL VS. PULLOUT RESISTANCE FOR SLIPPED TESTS

bolt. The nondestructive tests were not included in this graph because the results of a nondestructive test, would result in a trend line that is lower than the actual ultimate load of the bolt.

The plot of the mean values for the ultimate load for slipped tests shown in Table 2-19 indicates an extremely high R^2 value of 0.9973. This would indicate that the assumption regarding the influence of corrosion level of the bolt on the ultimate bearing capacity (positive up to a certain level of corrosion, then the strength of the bolt degrades and corrosion influence becomes negative), is correct. This result is also confirmed in Figure 2-38 where the slipped and broken tests are grouped together to examine the influence of corrosion on the combined groups of tests. The R^2 value is less than that for the slipped tests in Figure 2-37, however, there is still an obvious trend to the data.

These results, being qualitative in nature, are not as reliable as quantitative pieces of data, due to the inherent error at two stages in the recording and the interpretation of the data. When the data is recorded, the classification of the data is ambiguous and depends upon what the recorder of the information thinks is a "*very corroded*" bolt and what is "*surficial corrosion*". The second level of error occurs when this data is re-interpreted by a different person in order to convert each individual's classification into a standardized classification scheme. The second level of error could be avoided if everyone used a standardized scheme to record pull testing information.

Conclusions

The statistical data and the correlation coefficients, combined with what is previously known about the function and mechanisms of the Swellex bolt, lend credence to the conclusion that moderate corrosion improves the strength of the bolt. Excessive corrosion decreases the strength of the bolt. The point at which this occurs, requires further study and more data. A standardized quantitative method for recording corrosion information is required in order to improve the usefulness of the data. As well, pull testing personnel should make more of an effort to record corrosion information.

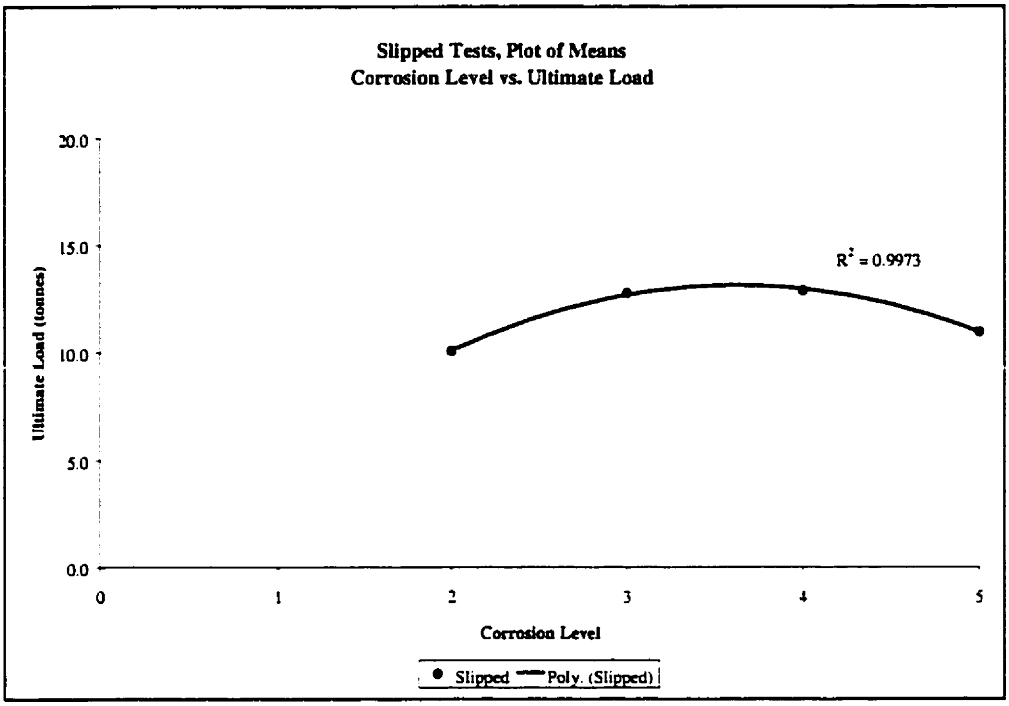

FIGURE 2-37: MEAN VALUES FOR ULTIMATE LOAD VS. CORROSION LEVEL FOR SLIPPED TESTS

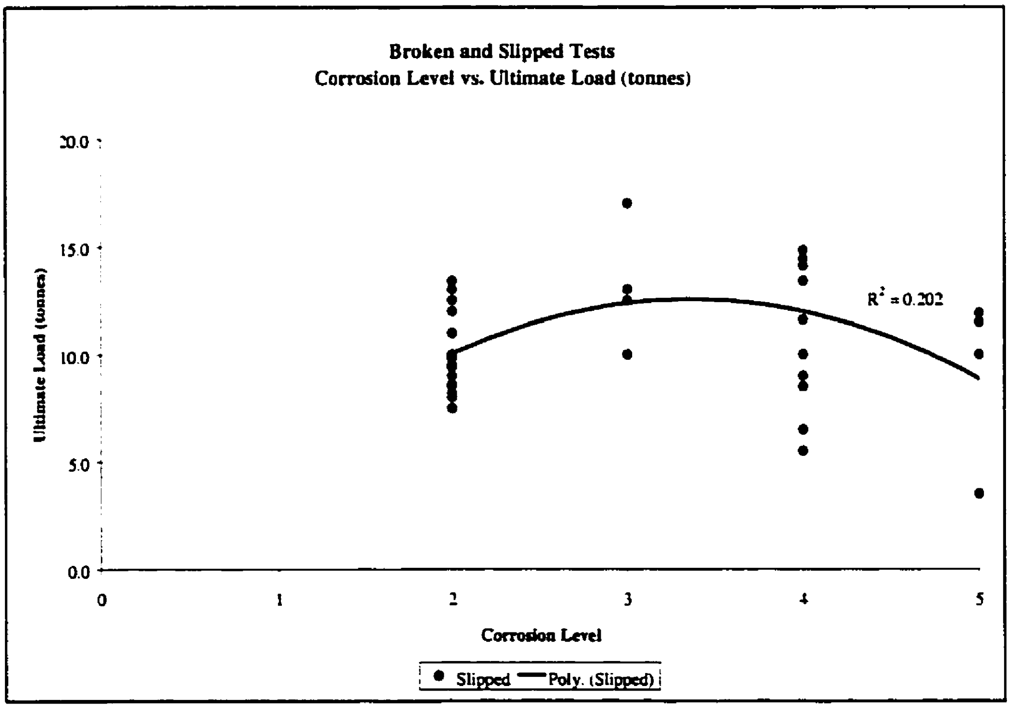

FIGURE 2-38: CORROSION LEVEL VS. ULTIMATE LOAD FOR SLIPPED AND BROKEN TESTS

2.9.2 Residence Time

An analysis was conducted on the residence time of the bolts. The residence time is defined as time between installation of the bolt and pull testing of the bolt. In order to obtain this number both the test date and the installation date had to have been recorded in the pull test information. The test date was recorded in 188 of the pull tests; however, the installation date was only recorded in 95 of the pull test records. Therefore, there were only 95 records (35% of the records), for which the age of the bolt could be calculated. This set of data was divided into the three different test types and a statistical analysis was performed on the data for each of the test types. The results are presented in the Table 2-20.

TABLE 2-20: SUMMARY STATISTICS FOR RESIDENCE TIME FOR ALL TEST TYPES

	All Tests		Slipped Tests		Nondestructive Tests		Broken Tests	
	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)
No. of Tests	95		50		30		15	
Mean	11.29	5.51	12.12	6.06	10.47	4.91	10.18	4.88
Standard Deviation	2.29	1.16	2.15	0.92	0.81	0.79	3.53	1.57

Broken Tests and Nondestructive

From Table 2-20, the mean ultimate load of the broken tests show that some bolts are breaking at well below the 10 tonnes breaking load suggested by the manufacturer. The nondestructive test results are of course entirely dependent upon the tester, and are shown purely as a minimum load which is being attained, which is reflected in the small standard deviation.

The pull test data was plotted for each of the test types, for the ultimate load and the pullout resistance. The results are shown in Figures 2-39 and 2-40. The correlation coefficients are insignificant for the nondestructive tests for both pullout resistance and ultimate load.

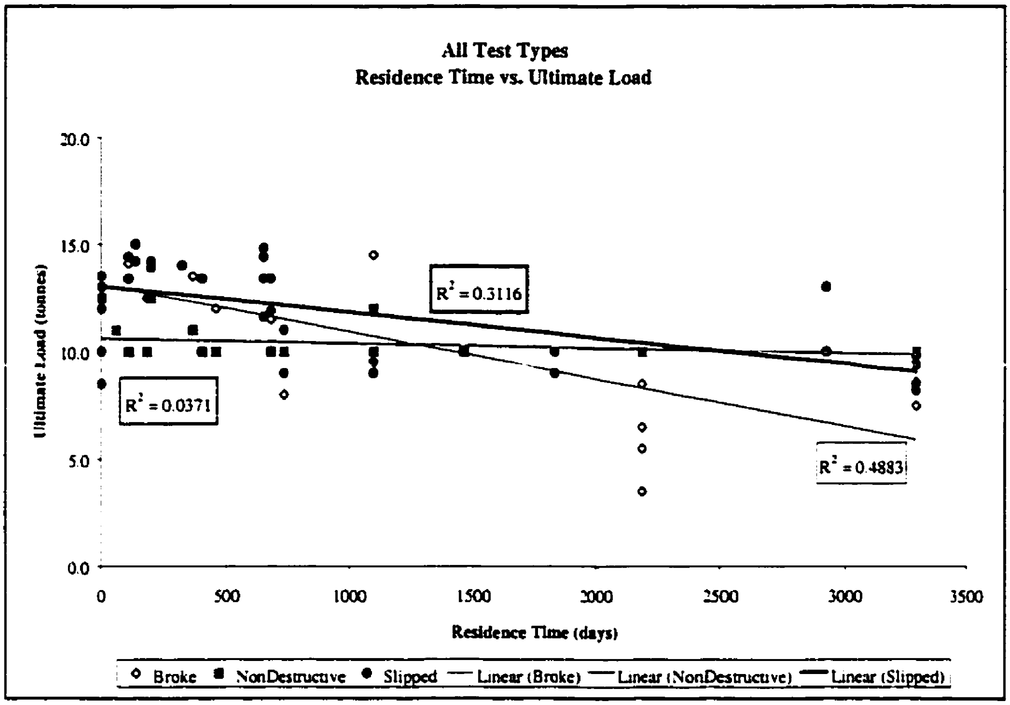

FIGURE 2-39: RESIDENCE TIME VS. ULTIMATE LOAD FOR ALL TEST TYPES

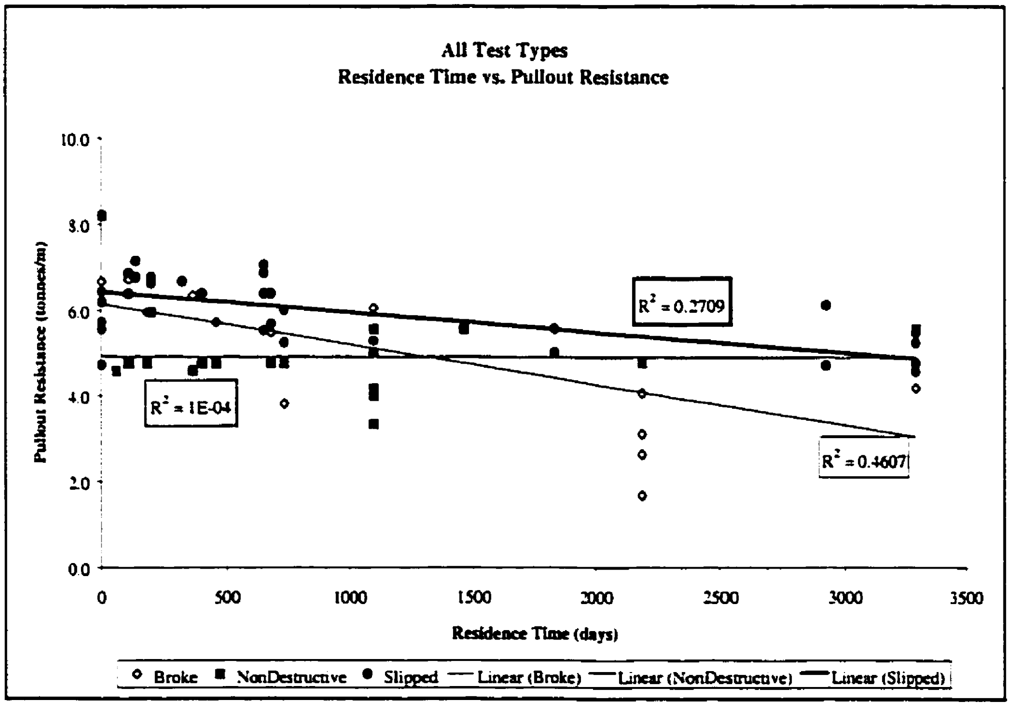

FIGURE 2-40: RESIDENCE TIME VS. PULLOUT RESISTANCE FOR ALL TEST TYPES

Slipped Tests

From Table 2-20, the minimum suggested slip load was obtained in the slipped tests. The slipped test results graphs are shown separately for clarity, in Figures 2-41 and 2-42. The correlation coefficients for the broken test were much higher at $R^2 = 0.4883$ and $R^2 = 0.4703$ for the ultimate load and the pullout resistance, respectively. This indicates that the age of the bolt does have an influence on the breaking load of the bolt; and the older the bolt is, the lower the breaking load. This trend can be attributed to the greater degree of exposure of the bolt over time, particularly to corrosion.

The trend lines for the slipped tests vs. residence time for both the ultimate load and the pullout resistance indicate the same general trend as the broken tests; that the performance of the bolt degrades with time. The correlation coefficients are lower than those of the broken tests, $R^2 = 0.3116$, and $R^2 = 0.2709$ for the ultimate load and the pullout resistance, respectively. However, they are still large compared to many of the other factors.

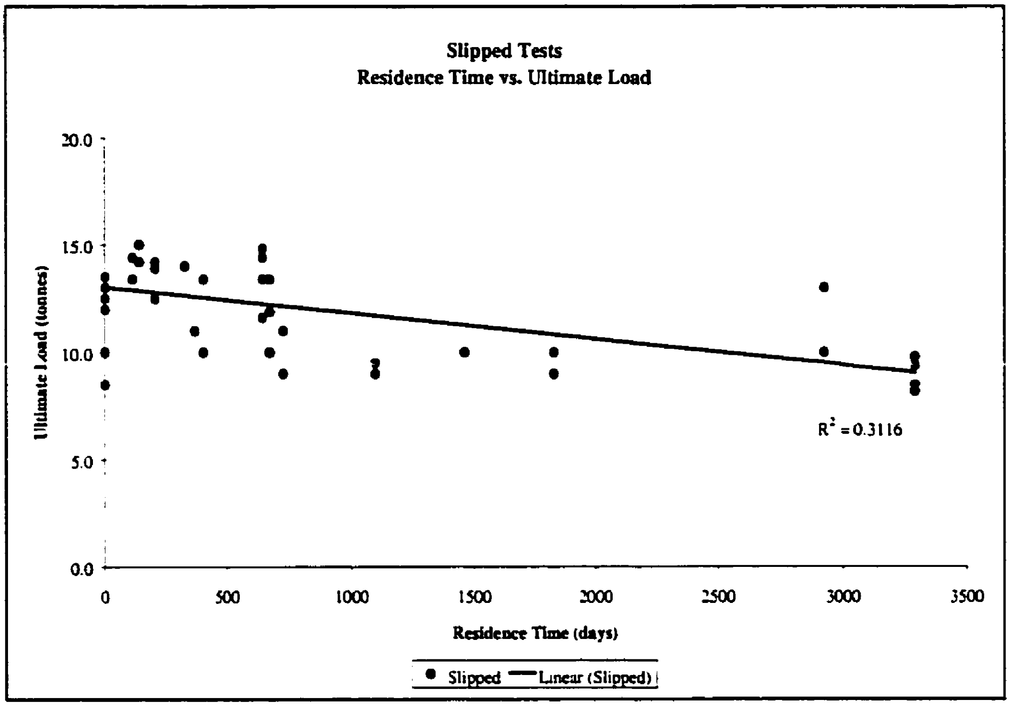

FIGURE 2-41: RESIDENCE TIME VS. ULTIMATE LOAD FOR SLIPPED TESTS

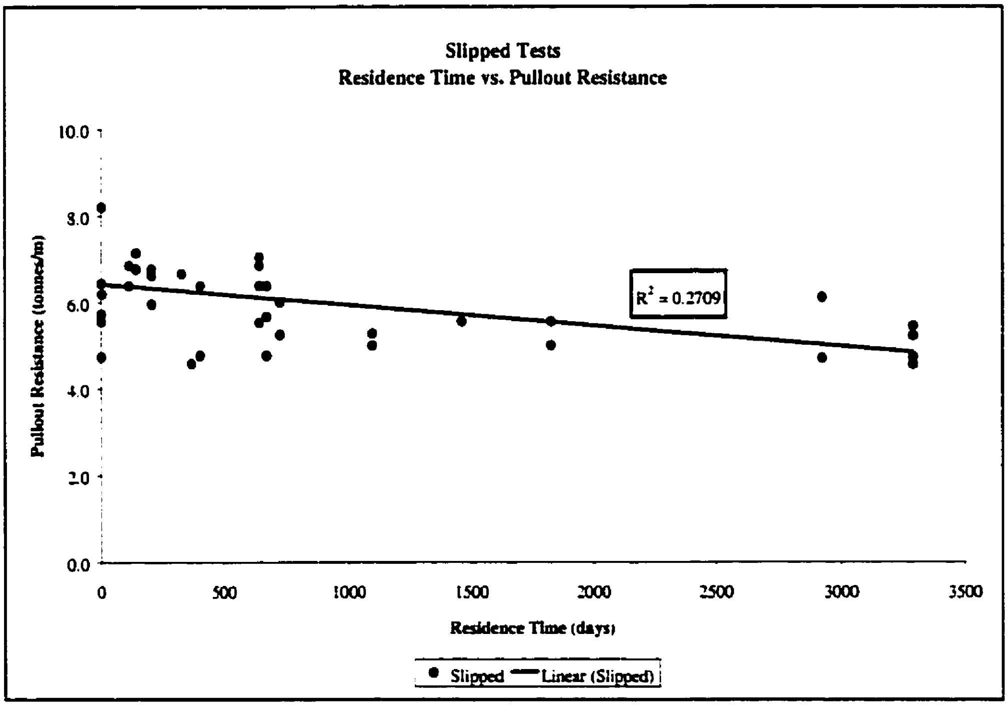

FIGURE 2-42: RESIDENCE TIME VS. PULLOUT RESISTANCE FOR SLIPPED TESTS

Test Date and Installation Date

The influence of both the test date and the installation date was analysed. As expected, there was no correlation for either one of these factors for slipped tests. The correlation coefficients were very low. There was a trend in the broken tests for installation date parameter, which had a correlation coefficient of $R^2 = 0.3893$. This may be the result of the underlying influence of the age of the bolt. Most of the test dates collected are from the last few years, while the installation dates are distributed over a number of years. The statistical analysis and the graphs are provided for interest on the following pages. It is interesting to note that the result of the analysis of the installation date data serves to validate the results from the residence time. It eliminates the possibility that the trend line is a reflection of underlying trends carried over from the either of the two factors from which the residence time is calculated.

TABLE 2-21: SUMMARY STATISTICS FOR TEST DATE FOR ALL TEST TYPES

	All Tests		Slipped Tests		Nondestructive Tests		Broken Tests	
	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)
No. of Tests	188		109		58		21	
Mean	11.11	5.28	11.53	5.60	10.45	4.74	10.78	5.10
Standard Deviation	2.39	1.99	2.51	2.31	1.54	1.26	3.21	1.48

TABLE 2-22: SUMMARY STATISTICS FOR INSTALLATION DATE ALL TEST TYPES.

	All Tests		Slipped Tests		Nondestructive Tests		Broken Tests	
	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)
No. of Tests	95		50		30		15	
Mean	11.29	5.51	12.12	6.06	10.47	4.91	10.18	4.88
Standard Deviation	2.29	1.16	2.15	0.92	0.81	0.79	3.53	11.57

Conclusions

The trend lines for the slipped tests vs. residence time for both the ultimate load and the pullout resistance indicate the same general trend as the broken tests, that the performance of the bolt degrades with time. The result can be most easily explained by the effect of exposure of the bolt over time. This trend line is not the result of an underlying trend carried from one or both of the two factors (installation date and test date) from which the residence time was obtained.

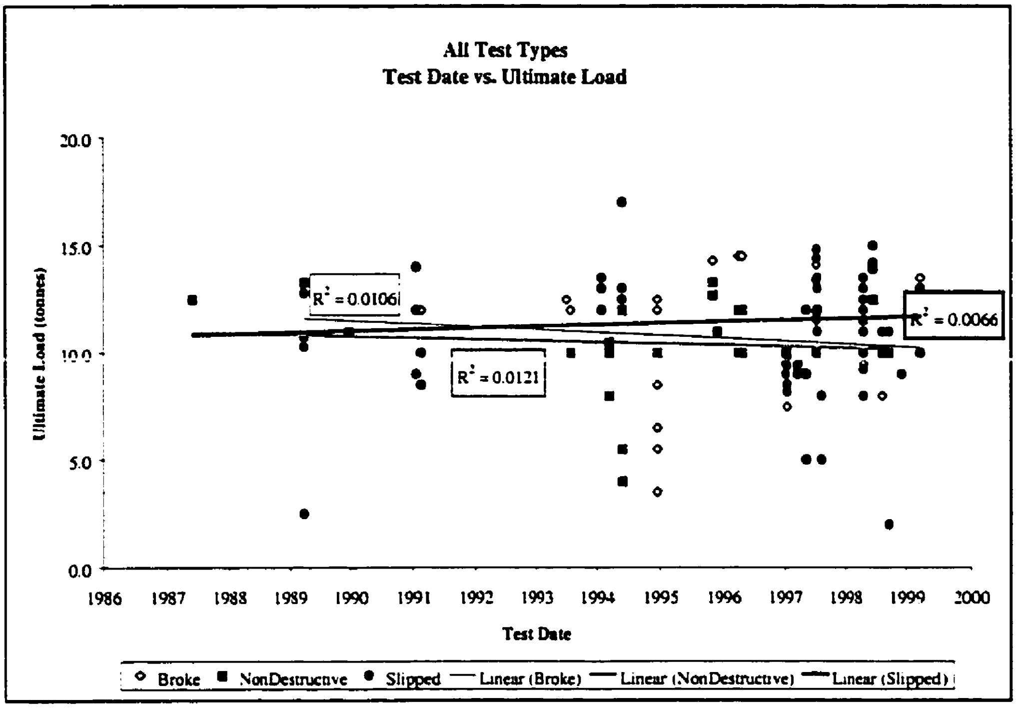

FIGURE 2-43: TEST DATE VS. ULTIMATE LOAD FOR ALL TEST TYPES

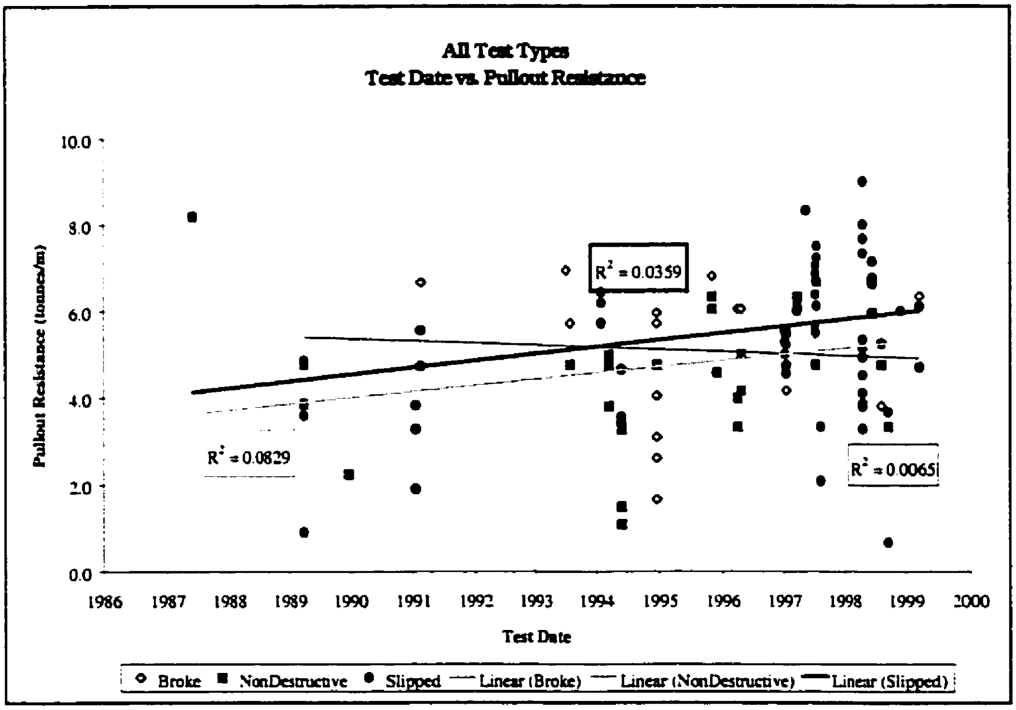

FIGURE 2-44: TEST DATE VS. PULLOUT RESISTANCE FOR ALL TEST TYPES

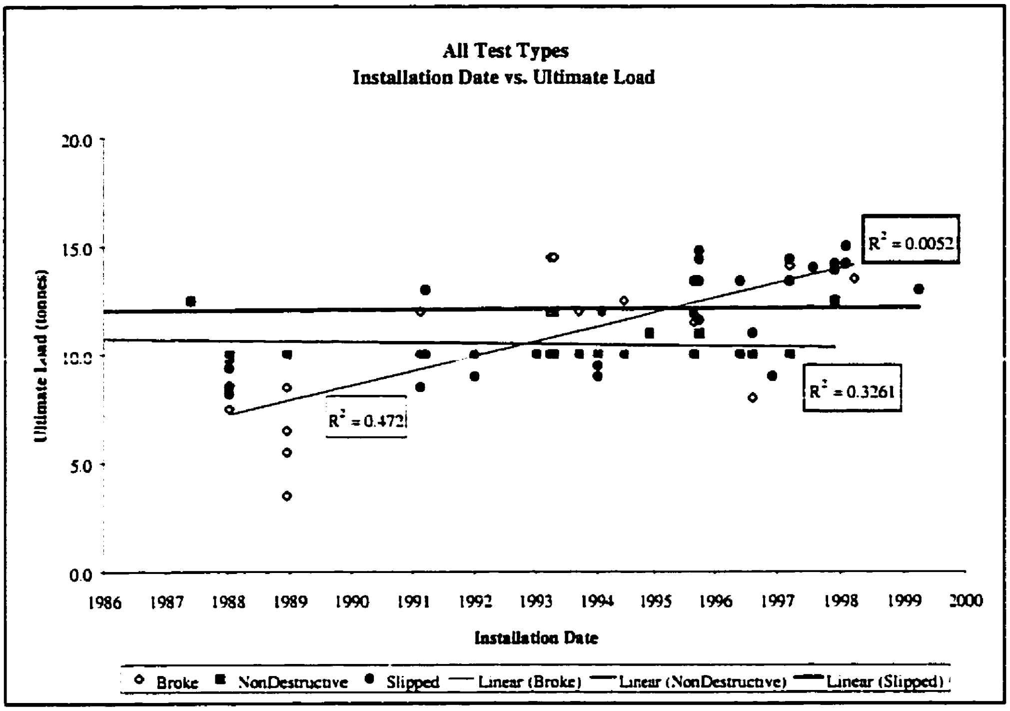

FIGURE 2-45: INSTALLATION DATE VS. ULTIMATE LOAD FOR ALL TEST TYPES

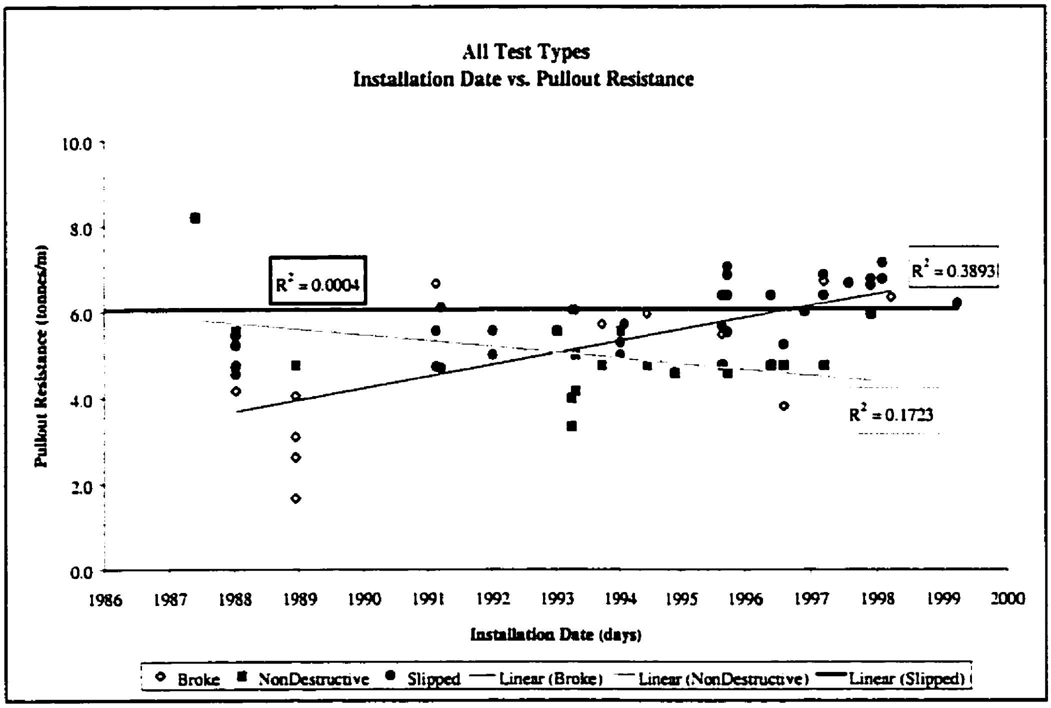

FIGURE 2-46: INSTALLATION DATE VS. PULLOUT RESISTANCE FOR ALL TEST TYPES

2.10 PARAMETERS ASSOCIATED WITH GROUND CONDITIONS

The rock mass in which a rock bolt is installed can have a significant influence on the performance of the bolt. The rock mass is an integral part of the anchoring system. Whether the bolt is frictional, mechanically anchored, or achieves its anchorage via a bonding agent such as a grout or resin, all of the mechanisms which hold the bolt in place interact with the rock mass.

Additionally, Swellex has a unique effect on weak and soft rock. The inflation of the bolt consolidates the surrounding rock mass and actually improves the load bearing capacity of the weak rock. Whether this effect works in reverse as well, (i.e. weak rock improves the performance of the Swellex bolt) is investigated in the following sections.

Some of the parameters which characterize the rock mass, are UCS, Young's Modulus, RQD, RMR, Q, water infiltration level and the lithology of the rock. Information for all of these factors was recorded in the pull test data. However, all of these factors were not recorded in all of the tests and, in most cases, the number of pull tests containing information for each factor is very small (Table 2-3). For each of these parameters a statistical analysis was performed on the available data, the data was plotted and trend lines were generated.

2.10.1 Elastic Modulus

The radial mechanical locking effect developed in a Swellex bolt is a result of the interaction of the elastic modulus of the steel in the bolt and the elastic modulus of the rock surrounding the bolt. Therefore, it stands to reason that the elastic modulus of the rock would have some influence on the performance of the bolt. The elastic modulus was only recorded in 26 of the total 275 pull test records (9%) of the pull tests records. 11 were slipped test results, 10 were nondestructive test results and 5 were broken test results. A statistical analysis was conducted on the pull tests data for the ultimate load and for the pullout resistance for each of the test types and for all the pull tests as a complete set. The results are presented in Table 2-23.

TABLE 2-23: SUMMARY STATISTICS FOR ELASTIC MODULUS FOR ALL TEST TYPES

	All Tests		Slipped Tests		Nondestructive Tests		Broken Tests	
	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)
No. of Tests	26		11		10		5	
Mean	10.97	6.06	9.73	7.43	11.44	4.55	12.76	6.06
Standard Deviation	2.57	3.79	3.31	5.38	1.29	1.69	1.08	0.50

The mean ultimate load for the broken tests is 12.76 with a standard deviation of 1.08, well above the suggested 11 tonnes. The mean ultimate load for the slipped tests was 9.73 tonnes with a standard deviation of 3.31 tonnes, which means that if this distribution was representative, the majority of the bolts are slipping at a load below the suggested 10 tonnes. The pull test results were plotted graphically. Linear trend lines were fitted through the data for each of the test types. R^2 values were calculated for each of the fitted trend lines. The results for the influence of elastic modulus on ultimate load are displayed in Figure 2-47 and for pullout resistance in 2-48. In the interest of clarity, Figures 2-49 and Figure 2-50 show the results for slipped tests alone.

Broken Tests

The broken-test trend line for the influence of elastic modulus on the ultimate load is horizontal indicating that elastic modulus has little influence on the breaking load of the bolt. The same result is found in the pull out resistance graph, Figure 2-48. The correlation coefficients, R^2 were high for both the ultimate load and for the pullout resistance trend lines. However, there were very few pull tests in this subset (only 5), which is not enough to obtain a statistically meaningful result.

Slipped Tests

The slope of the trend line for slipped tests for the influence of elastic modulus on the ultimate load is negative, indicating that increasing elastic modulus has a negative influence on the slip load of the bolt (i.e., as the elastic modulus increases, the slip load decreases). The R^2 value for this trend line was 0.3981. The same result is found in the pull out resistance graph, Figure 2-50. Although the correlation coefficients are relatively high, there are only 11 pieces of data in this set, which is not enough to obtain a meaningful result. There was no observable trend in the tests that failed below the manufacturer's suggested minimum of 10 tonnes. The failed tests are evenly distributed among the different elastic modulus values.

Conclusions

The pull test data available indicates that an increase in the elastic modulus has a negative influence on both the breaking load and the slip load of the bolt. However, there is too little data to obtain a statistically meaningful result. Because of the manner in which the Swellex bolt interacts with the surrounding rock material during the installation of the bolt, some influence is expected. The determination of the exact nature of the influence requires more data. These results are further discussed in the third section of this thesis.

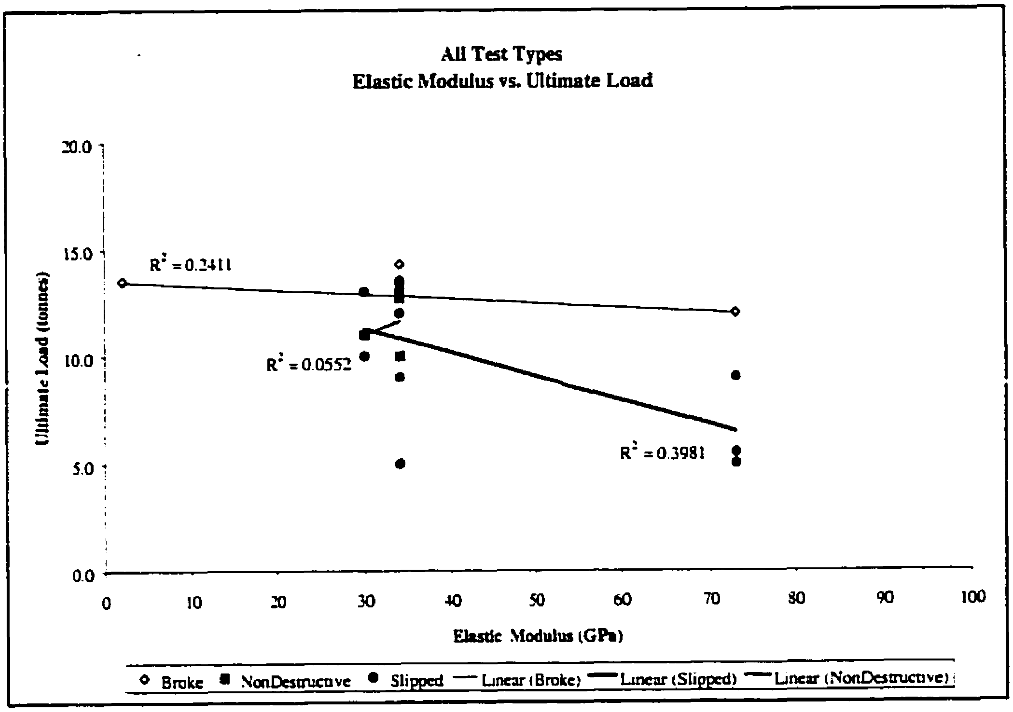

FIGURE 2-47: ELASTIC MODULUS VS. ULTIMATE LOAD FOR ALL TEST TYPES

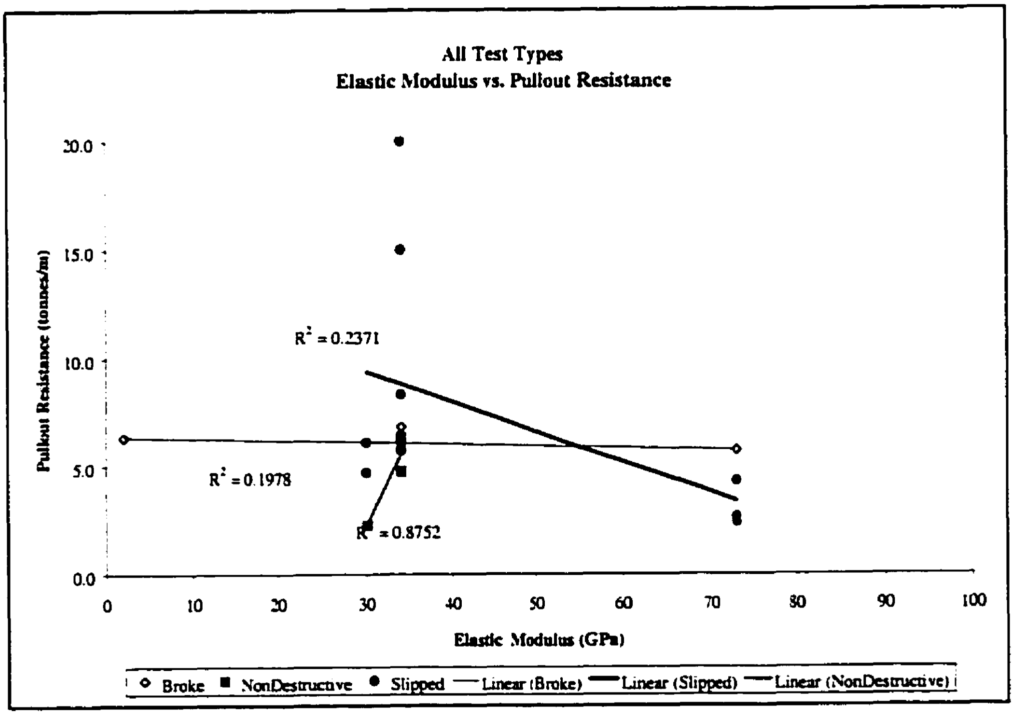

FIGURE 2-48: ELASTIC MODULUS VS. PULLOUT RESISTANCE FOR ALL TEST TYPES

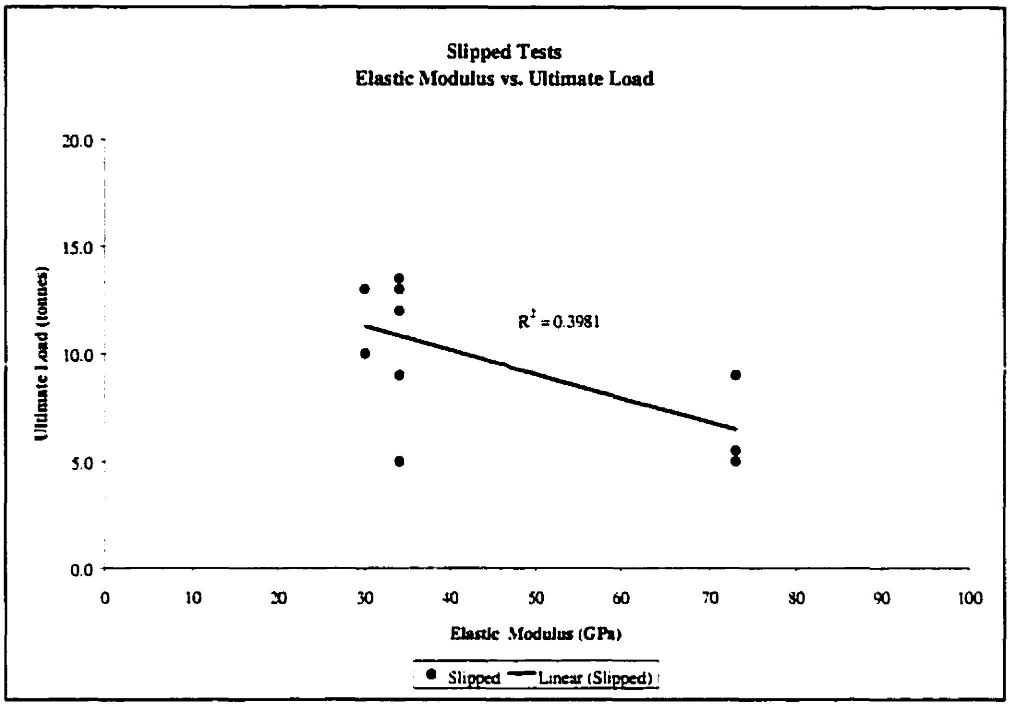

FIGURE 2-49: ELASTIC MODULUS VS. ULTIMATE LOAD FOR SLIPPED TESTS

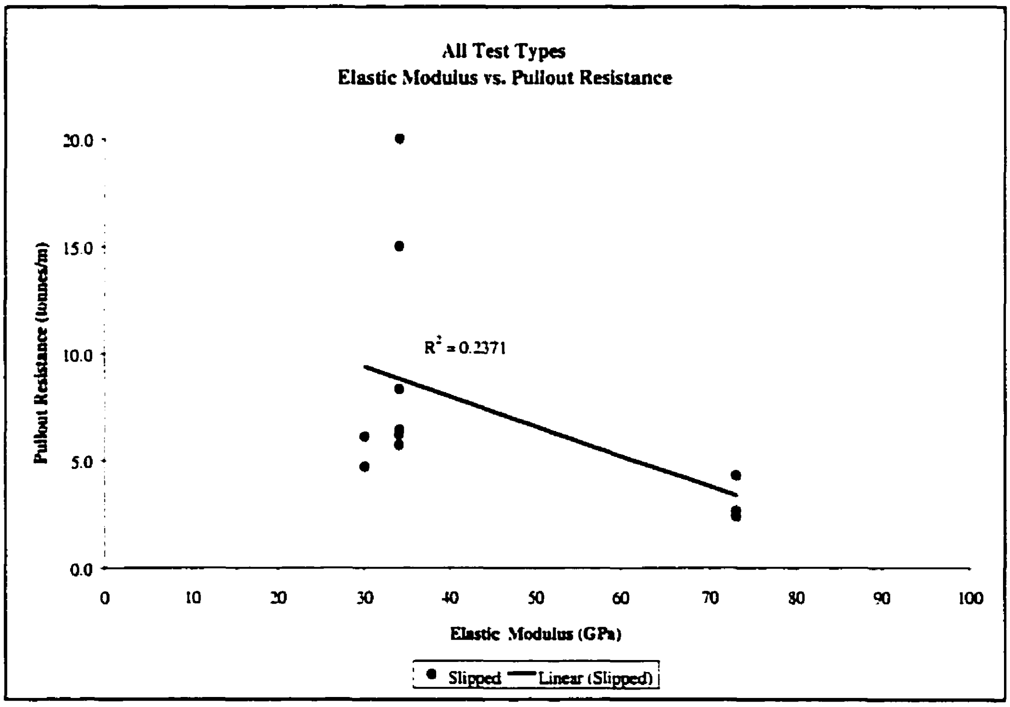

FIGURE 2-50: ELASTIC MODULUS VS. PULLOUT RESISTANCE FOR SLIPPED TESTS

2.10.2 Uniaxial Compressive Strength

Atlas Copco Ltd. suggests that the Swellex bolt improves the condition of the interfacing rock and increases its load bearing capacity. This effect occurs because of the consolidation of material resulting from the expansion of the Swellex bolts.[17] Swellex may have an effect on rock strength, but does rock strength effect the performance of Swellex? A number of factors influence the quality of the ground conditions. This section deals with the influence of the Uniaxial Compressive Strength (UCS) of the rock. UCS data was recorded in 69 of all the pull test records (approximately 25%). This value was much lower initially, so the respondents were contacted and some were able to provide subsequent information to fill out this area of the data. The pull test data was analysed statistically and the mean and standard deviation was calculated for all of the bolts together and for each of the test types individually. The results are presented in Table 2-24.

TABLE 2-24: SUMMARY STATISTICS FOR UCS FOR ALL TEST TYPES

	All Tests		Slipped Tests		Nondestructive Tests		Broken Tests	
	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)
No. of Tests	69		34		20		15	
Mean	10.87	6.76	9.42	6.37	12.30	6.69	12.24	7.21
Standard Deviation	3.48	3.54	3.75	3.25	3.01	4.43	1.80	2.79

There is a large standard deviation in the slipped test data, and in the broken test data. However, only 2 of the 15 broken tests failed below the suggested 10 tonnes, whereas 14 of the 34 slipped test failed below the suggested minimum slip load of 10 tonnes. The pull test data was also plotted in graphical form for both the ultimate load and for pullout resistance. Linear regression was used to fit linear trend lines through the data points. R^2, the correlation coefficient value was also calculated for each of the trend lines. The results are presented in Figures 2-51 through 2-54.

Broken and Nondestructive Tests

The linear trend line for the influence of UCS on the ultimate load in broken tests has a correlation coefficient of $R^2 = 0.3503$ and indicates that the ultimate load of the bolt decreases in broken tests with an increase in UCS. The linear trend line for pullout resistance indicates the opposite, the pullout resistance increases with an increase in UCS. The R^2 value for this trend line is 0.2923. It is difficult to determine what influence the UCS should have on the breaking strength of the bolt. Despite the relatively high correlation coefficients, the influence of UCS on the broken tests is

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[17] Atlas Copco Ltd., Swellex Product Manual, Swellex – The engineered rock reinforcement system, p.3

suspect for two reasons. The first is that there are only 15 data points for the broken tests, which does not provide a statistically reliable result. Secondly, in both the ultimate load and the pullout resistance the effect is not highly sensitive to UCS. An increase in UCS of 200 MPa results in a decrease in the ultimate load of 2 tonnes, and an increase in pullout resistance of 2.5 tonnes/m. The minimum value of ultimate load and pullout resistance for both the low UCS and the high UCS values are still well above the suggested breaking load of steel. Again, the trend lines for nondestructive tests reflect the influence of the tester and the effect of other influences, such as UCS, are not apparent.

Slipped Tests

The results from the pull test analysis show UCS does have an influence on the slip load of the bolt. The linear trend line that was fitted though the ultimate load vs. UCS for the slipped tests indicates that an increase in UCS results in an increase in ultimate load. The trend line has a correlation coefficient of $R^2 = 0.2314$. The result is the same for the pullout resistance vs. UCS trend line with a correlation coefficient of $R^2 = 0.0876$. Despite the lower R^2 value in the pullout resistance, this result makes more sense. The load bearing capacity of the bolt is only moderately affected by the UCS. An increase in UCS of 300 MPa results in an increase in ultimate load of 5.5 tonnes. However, the strength of the rock mass has little effect on both the mechanical locking effect or on the frictional resistance generated along the length of the bolt.

A trend was noticed in the bolts that were slipping under 10 tonnes. Many of these bolts were clustered around the low UCS range of 0 to 40 MPa. UCS should have some influence on bolts installed in low strength rock, specifically in rocks with a UCS value lower than the pump pressure (generally 30 MPa). For these rocks, the inflation of the bolt will cause plastic deformation, not elastic deformation around the borehole periphery. The rock will not fully squeeze back onto the bolt when the pump pressure is released and mechanical locking will not occur. The zone of plastic deformation increases with the difference in pump pressure and UCS. The larger the plastic zone, the smaller the elastic response of the rock, which results in a lowered mechanical lock on the bolt. The only mechanism holding the bolt in place will be the axial friction. In order to test this hypothesis, a logarithmic trend line was fitted through the data using regression techniques. The correlation coefficient for this trend line (Figure 2-53) was much higher than the linear trend line ($R^2 = 0.4183$ vs. $R^2 = 0.2314$). This trend also indicates that beyond the 30 to 40 MPa range, an increase of 200 MPa results in a 1 tonne increase in ultimate bearing capacity. This result is more logical than the relationship shown by the linear trend line.

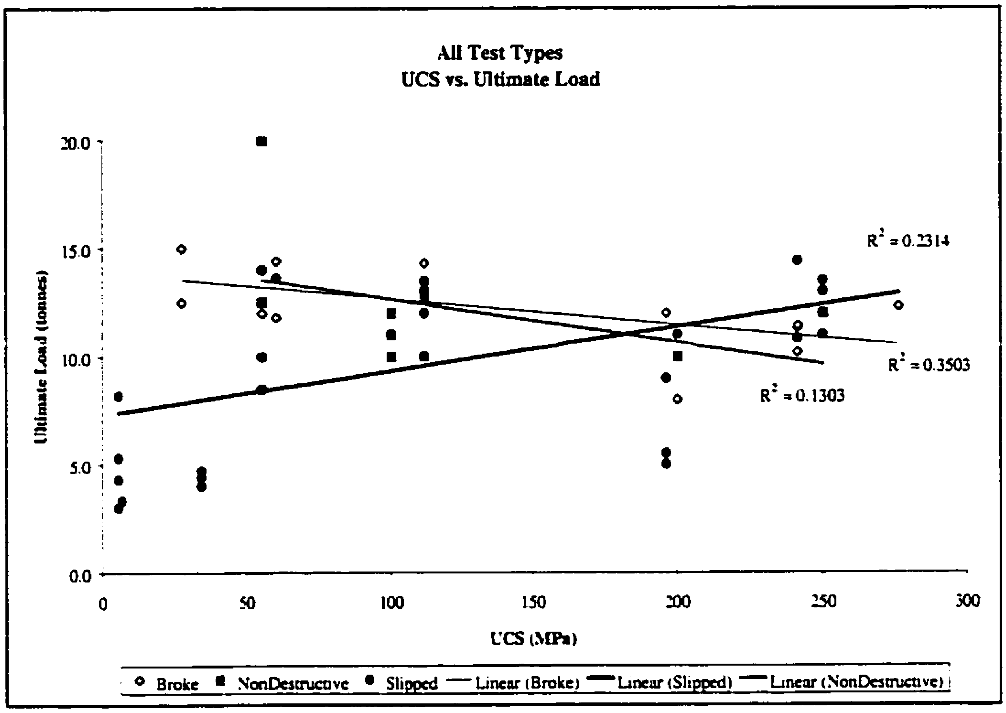

FIGURE 2-51: UCS VS. ULTIMATE LOAD FOR ALL TEST TYPES

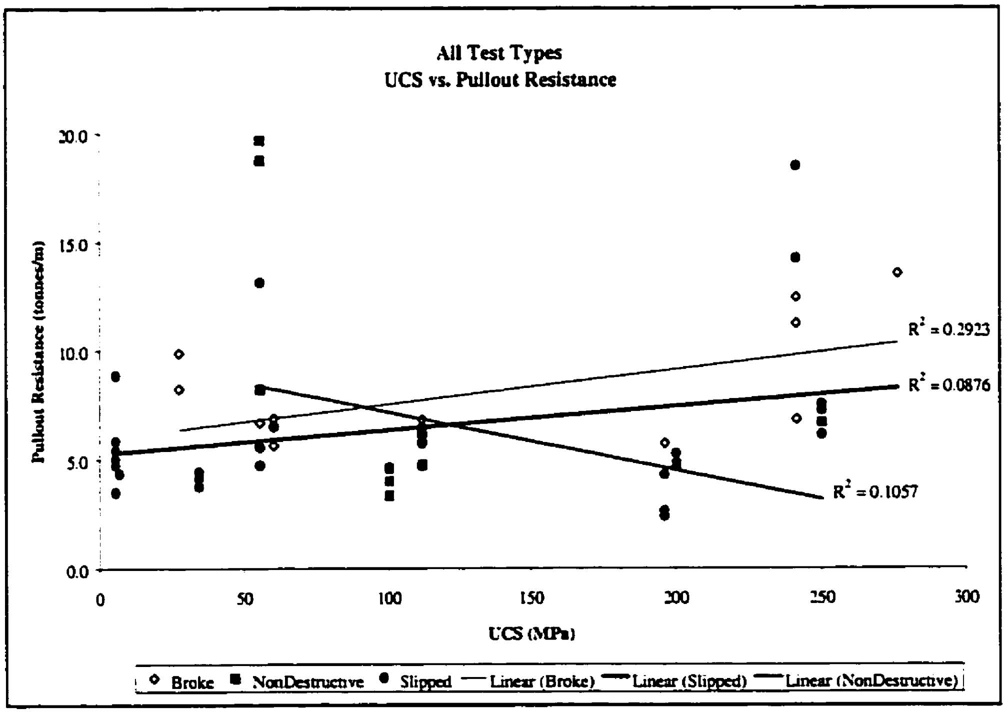

FIGURE 2-52: UCS VS. PULLOUT RESISTANCE FOR ALL TEST TYPES

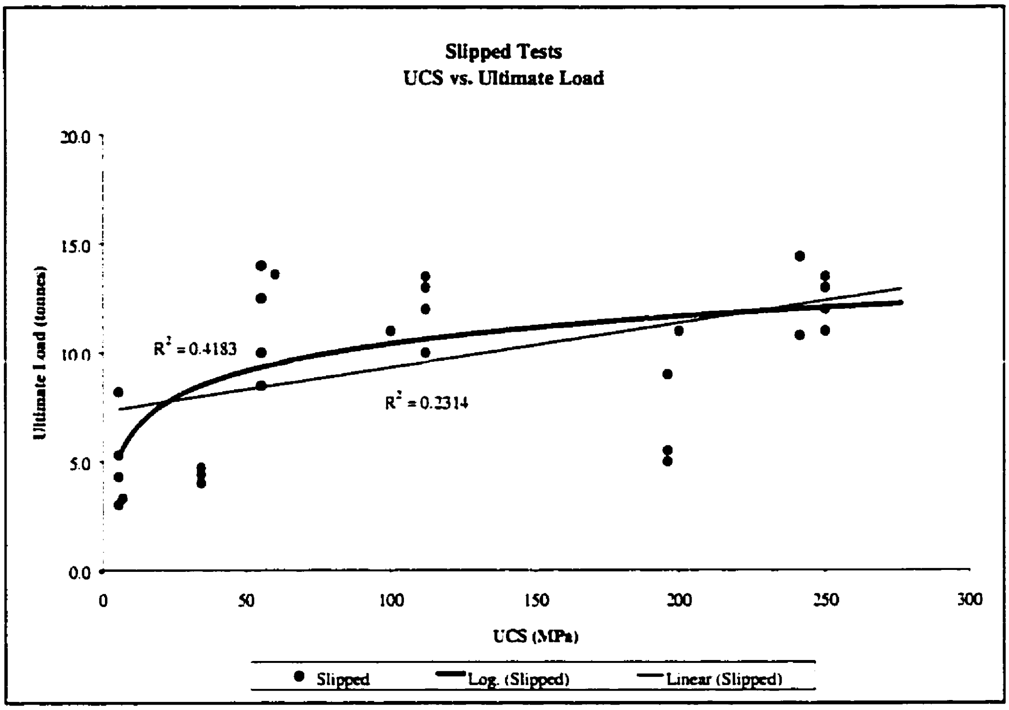

FIGURE 2-53: UCS VS. ULTIMATE LOAD FOR SLIPPED TESTS

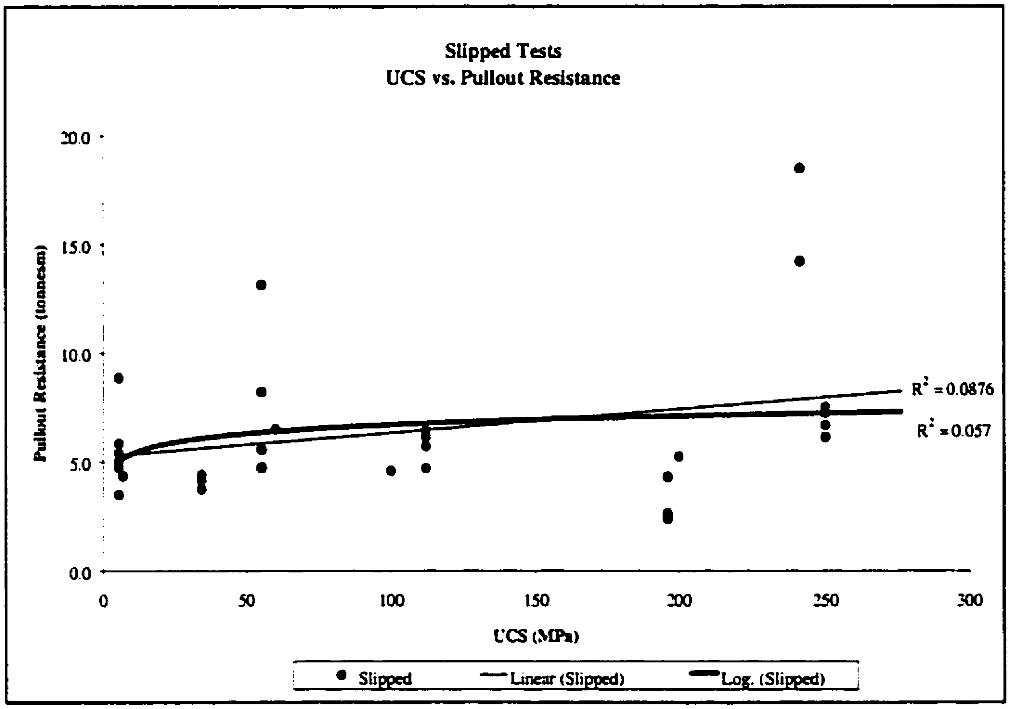

FIGURE 2-54: UCS VS. PULLOUT RESISTANCE FOR SLIPPED TESTS

Conclusions

According to the pull test data, UCS affects the ultimate load and pullout resistance of the Swellex bolt significantly for rocks with a UCS lower than the pump pressure (30 MPa). Beyond that range UCS has little influence. More data is required, as there were only 34 pieces of slipped test data and 15 pieces of broken tests data, to confirm this result, and to better determine whether UCS influences the breaking load of the bolt.

2.10.3 Water Conditions

One of the factors that contributes to the overall quality of ground conditions in a mine is the level of water infiltration. It is one of the factors in the Rock Mass Rating (RMR) system and in the GSI classification system. In the Swellex product manual, Atlas Copco Ltd. suggests that the bolt is unaffected by the presence of water which is squeezed out of the contact rock during installation of the bolt. In order to test the validity of that statement, an analysis was conducted on the pull test data with respect to the level of water infiltration in the rock.

The level of water infiltration was recorded in 64 of the total 304 pull test records, approximately 24% of the records. The information that was recorded was qualitative and non-standardized. For the purposes of this study, and in order to rank the data for analysis, a ranking system was used which incorporated the terminology that was commonly used by the testing personnel. The ranking system that was used is listed below:

- 1 = *Dry*
- 2 = *Damp*
- 3 = *Very Damp*
- 4 = *Dripping Water*
- 5 = *Flowing Water*

The data was then interpreted to fit this ranking system. The interpreted data was analysed statistically and the results are presented in Table 2-25. The mean and standard deviation was calculated for each of the three test types and for the all of the test types together.

TABLE 2-25: SUMMARY STATISTICS FOR WATER LEVEL FOR ALL TEST TYPES

	All Tests		Slipped Tests		Nondestructive Tests		Broken Tests	
	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)
No. of Tests	64		33		22		9	
Mean	11.01	5.86	11.12	6.46	10.75	5.11	11.28	5.50
Standard Deviation	2.00	2.32	2.29	3.04	1.10	0.59	2.63	1.07

Broken and Nondestructive Tests

The mean breaking load of the 9 broken tests is 11.28 tonnes with a standard deviation of 2.63 tonnes, which means that a significant number of these 9 bolts (3 bolts), are failing below the suggested 11.0 tonnes breaking load. However, this is a very small set of tests. Again, the nondestructive test results are provided as a minimum load that is being attained for these tests.

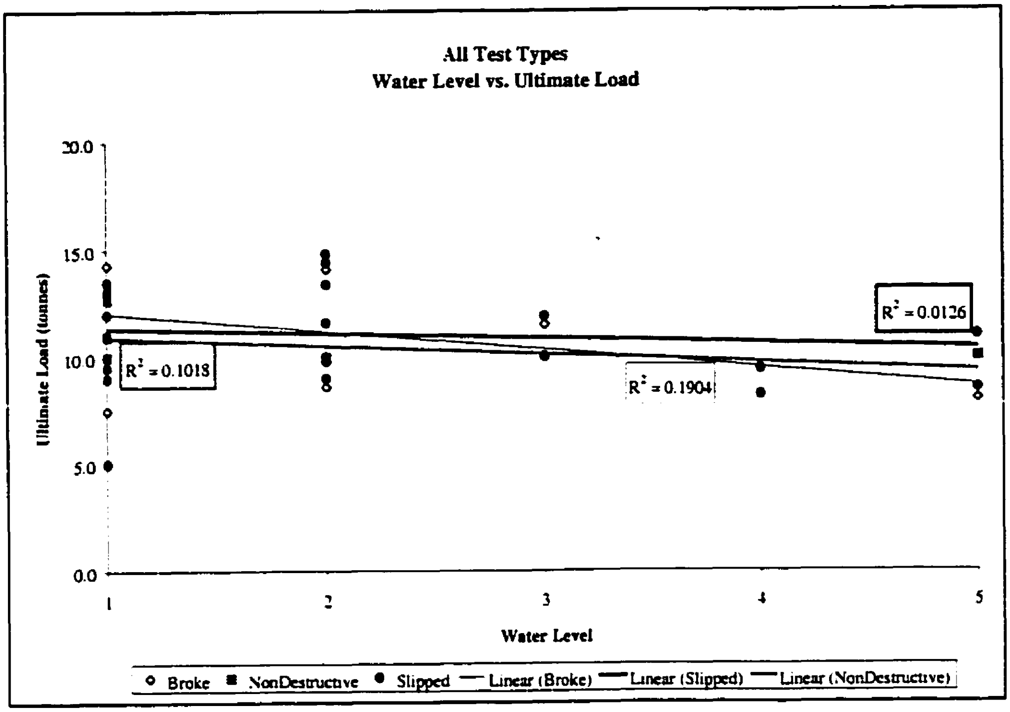

FIGURE 2-55: WATER LEVEL VS. ULTIMATE LOAD FOR ALL TEST TYPES

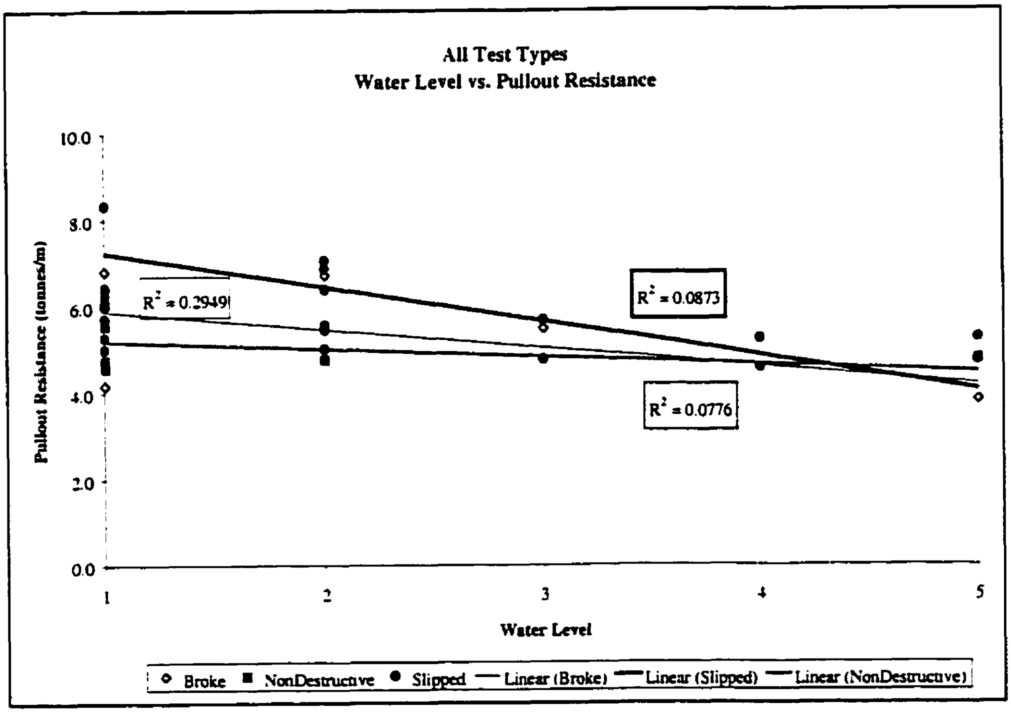

FIGURE 2-56: WATER LEVEL VS. PULLOUT RESISTANCE FOR ALL TEST TYPES

The pull test data was plotted graphically in Figure 2-55 and Figure 2-56. The horizontal axis represents the ranking system described previously in this section. The correlation coefficient, $R^2 = 0.0776$ was small for the nondestructive tests for both ultimate load and the pullout resistance, as expected. The correlation value for the broken tests was $R^2 = 0.1904$ for the ultimate load trend line and $R^2 = 0.2949$ for the pullout resistance trend line. These correlation coefficients are significant in relation to the other factors in this study and the trend line indicates that the ultimate breaking load decreases with increasing water infiltration. This result makes sense, especially in consideration of the results from analysis of the influence of the level of corrosion on the performance of the Swellex bolt. Increased corrosion level, results in a lowered ultimate breaking load. The two factors are interrelated, because water infiltration often causes corrosion.

Slipped Tests

TABLE 2-26: SUMMARY STATISTICS FOR WATER LEVEL FOR SLIPPED TESTS

	All		Dry		Damp		Very Damp		Dripping Water		Flowing Water	
	Load	Resist	Load	Resist	Load	Resist	Load	Resist	Load	Resist	Load	Resist
No. of Tests	33		13		14		2		2		2	
Mean	11.12	6.46	10.46	7.61	12.29	6.01	10.95	5.21	8.80	4.89	9.75	4.98
Standard Deviation	2.29	3.04	2.32	4.61	2.11	0.82	1.34	0.64	0.85	0.47	1.77	0.36

The mean and standard deviation were calculated for each of the levels of water infiltration for the slipped tests. The results were presented in Table 2-26. The pull tests results for ultimate load and pullout resistance were also plotted against the level of water infiltration and these results along with their associated trend lines and R^2 values were presented in Figure 2-57 and Figure 2-58. In the ultimate load vs. water level graph, the trend line is almost horizontal and the R^2 value is very low, indicating that water level has little influence on the ultimate load. The trend line in the pullout resistance shows a decrease in pullout resistance with an increase in water level. The R^2 value is higher, but still rather low at $R^2 = 0.0873$.

Intuitively, the trend in the pullout resistance is the logical one. There are three reasons for the low correlation coefficients and a horizontal trend line in the ultimate load chart. The first reason is the large amount of error associated with lumping the data into discrete categories. The mean values of each category have been used in Figure 2-59 in order to clarify the plot. The second reason is the interpretation required to categorize the data. Some data may not have been interpreted correctly. The third reason is the lack of data. There are only 2 pull test records in each of the very damp, dripping and flowing water categories.

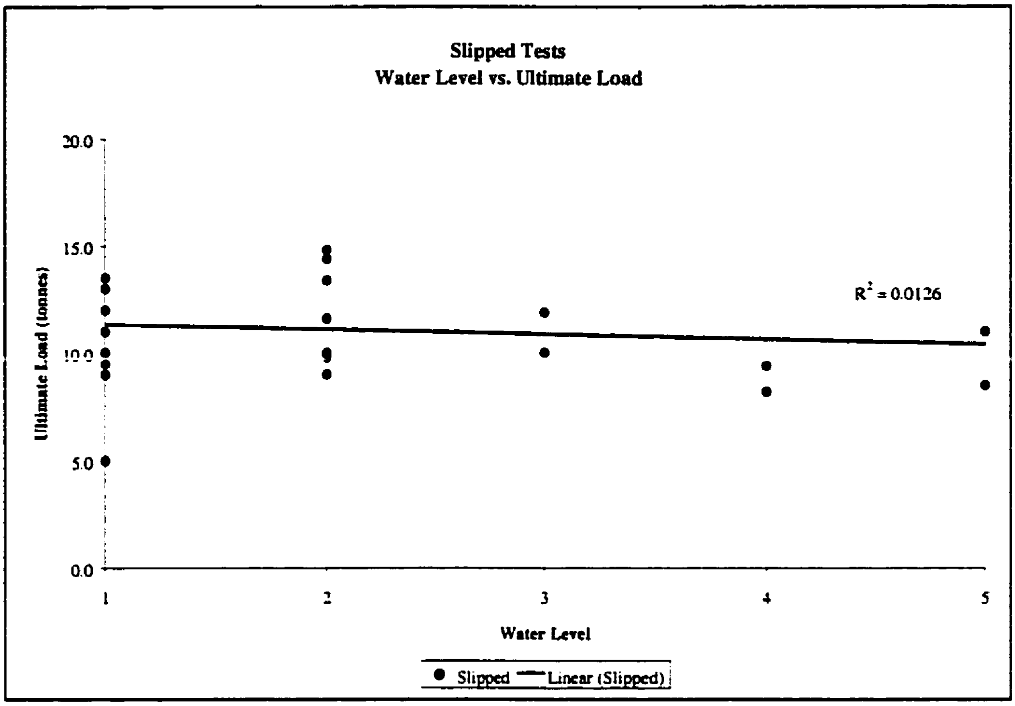

FIGURE 2-57: WATER LEVEL VS. ULTIMATE LOAD FOR SLIPPED TESTS

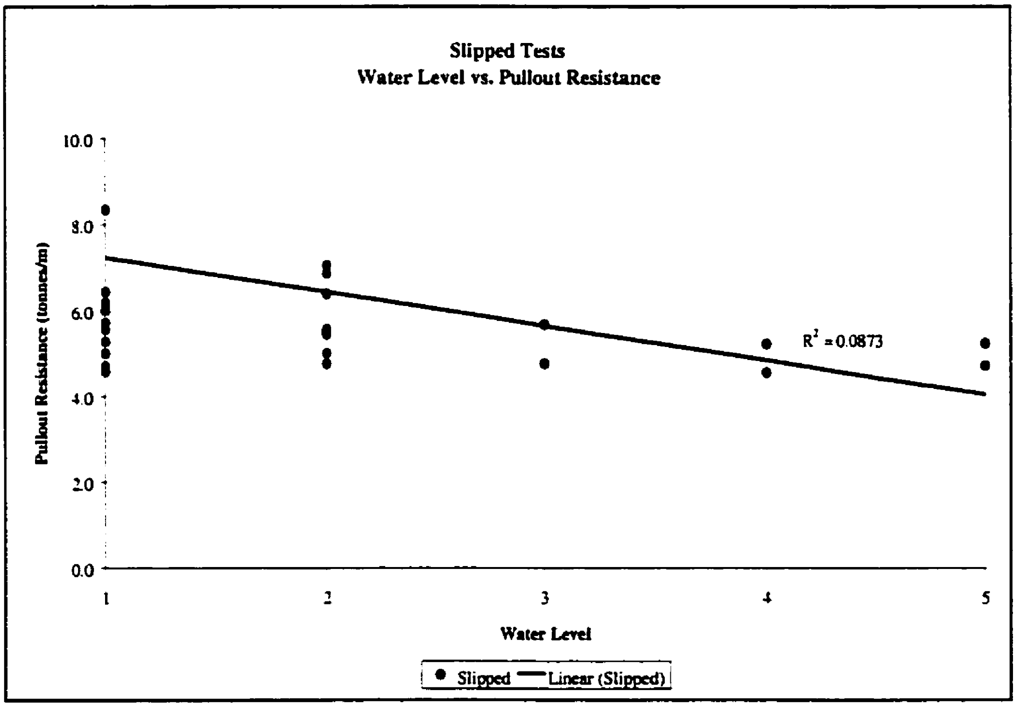

FIGURE 2-58: WATER LEVEL VS. PULLOUT RESISTANCE FOR SLIPPED TESTS

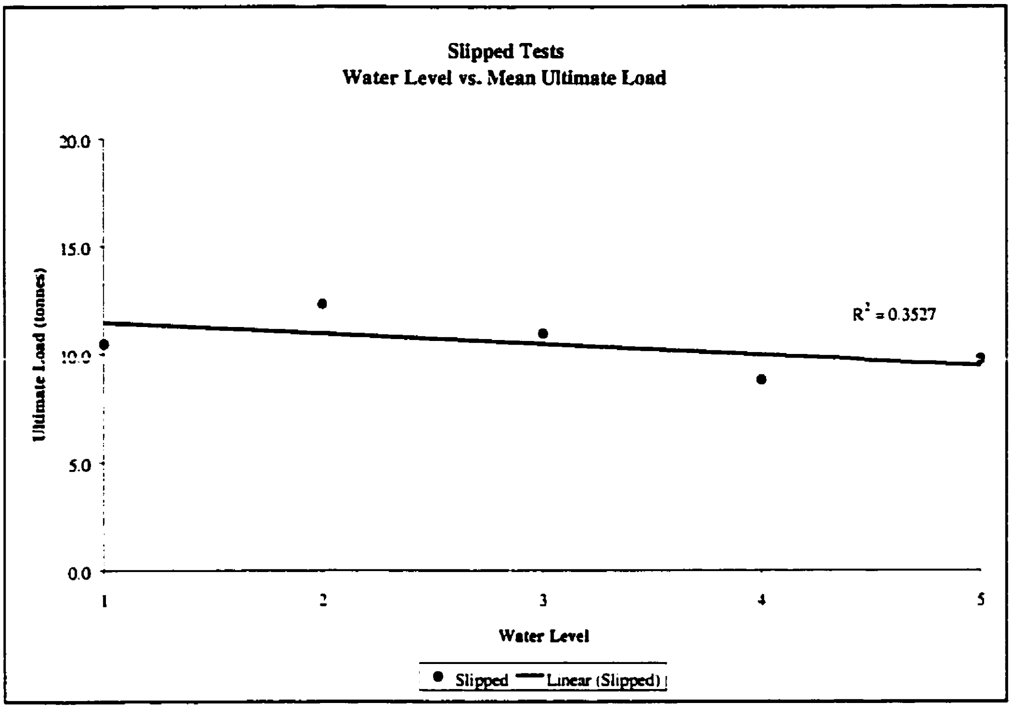

FIGURE 2-59: MEAN ULTIMATE LOAD FOR EACH OF THE 5 WATER INFILTRATION LEVELS FOR SLIPPED TESTS

Conclusions

The broken tests trend lines show a decrease in breaking strength with water level for both pullout resistance and ultimate load. The slipped test trend line for pullout resistance shows a decrease in breaking strength with water level. The trend line for ultimate load does not show the same trend. The decrease in strength for broken tests is logical because the effect of corrosion on the tensile strength of steel is the major determinant for breaking strength. Logically, increasing water level should decrease the bearing capacity of the bolt. However, it is difficult to determine what influence water level should have on slipped tests. Clearly, more data is required as well as a standard method of recording the water infiltration so as to eliminate some of the confusion surrounding the use of qualitative terms.

2.10.4 Rock Mass Rating

Very few of the pull test records initially contained information about the Rock Mass Rating. Even after a subsequent effort to fill out the information provided, only 37 of 275 the pull test records (13% of the total) contained RMR information. A statistical analysis was conducted on the data. The mean and standard deviation were calculated for each of the test types and for the all of the data as a whole set. The results are presented in Table 2-27. The pull test results were plotted graphically for the ultimate load vs. RMR and for pullout resistance vs. RMR. A linear trend line was fitted through the data for each of the test types. The correlation coefficient, R^2 was calculated for each trend line. The results are presented in Figures 2-60 and 2-61. In addition, Figure 2-62 and Figure 2-63 show the results for the slipped tests alone for clarity. It is important to note that there were only 15 records with pull test information pertaining to RMR, for slipped tests and most of these were clustered around the 73-75 RMR value. The analysis of the limited amount of data available is presented for interest, although the clustering around the 73-75 value of RMR, makes the results statistically questionable.

TABLE 2-27: SUMMARY STATISTICS FOR ROCK MASS RATING FOR ALL TEST TYPES

	All Tests		Slipped Tests		Nondestructive Tests		Broken Tests	
	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)
No. of Tests	37		15		16		6	
Mean	11.30	5.93	10.33	7.16	11.40	4.71	13.47	6.11
Standard Deviation	2.43	3.29	3.19	4.68	1.17	1.56	1.19	0.42

Conclusions

There is insufficient data in this area to provide any meaningful results or trends. The only conclusion that can be drawn is that RMR is rarely recorded and an effort should be made to record this information at the time of pull testing as it is readily available and may be valuable.

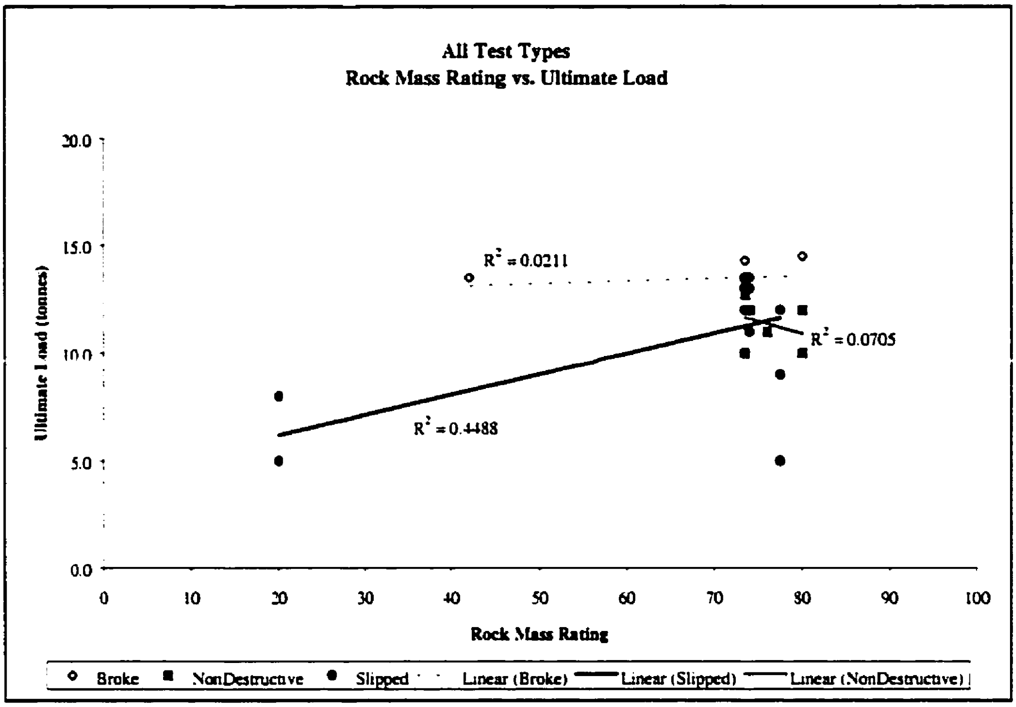

FIGURE 2-60: ROCK MASS RATING VS. ULTIMATE LOAD FOR ALL TEST TYPES

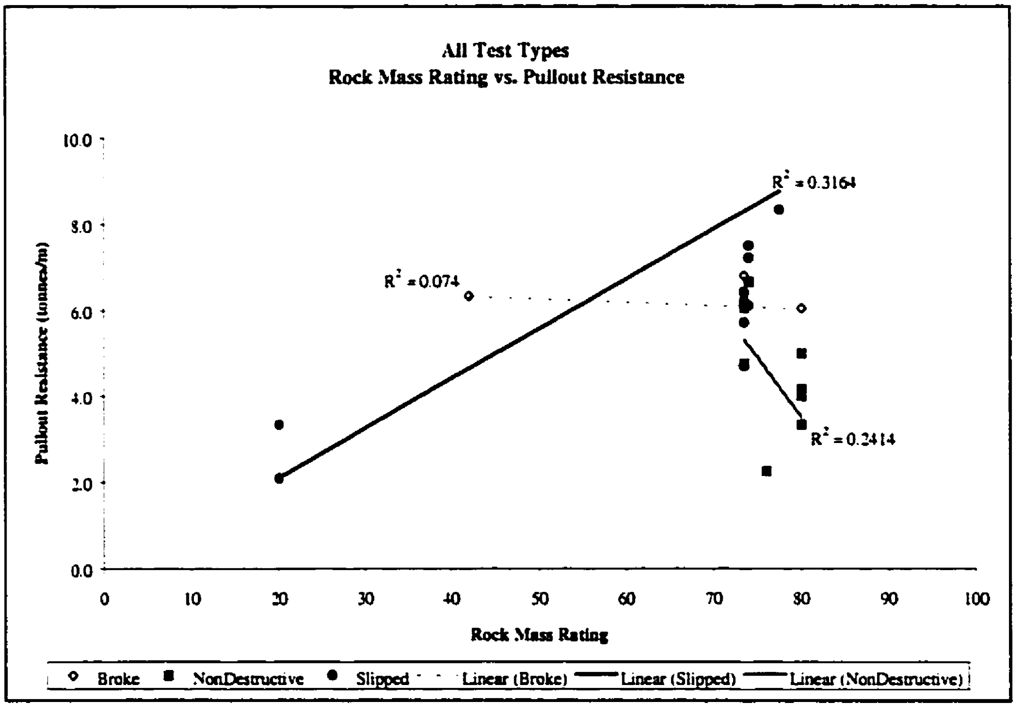

FIGURE 2-61: ROCK MASS RATING VS. PULLOUT RESISTANCE FOR ALL TEST TYPES

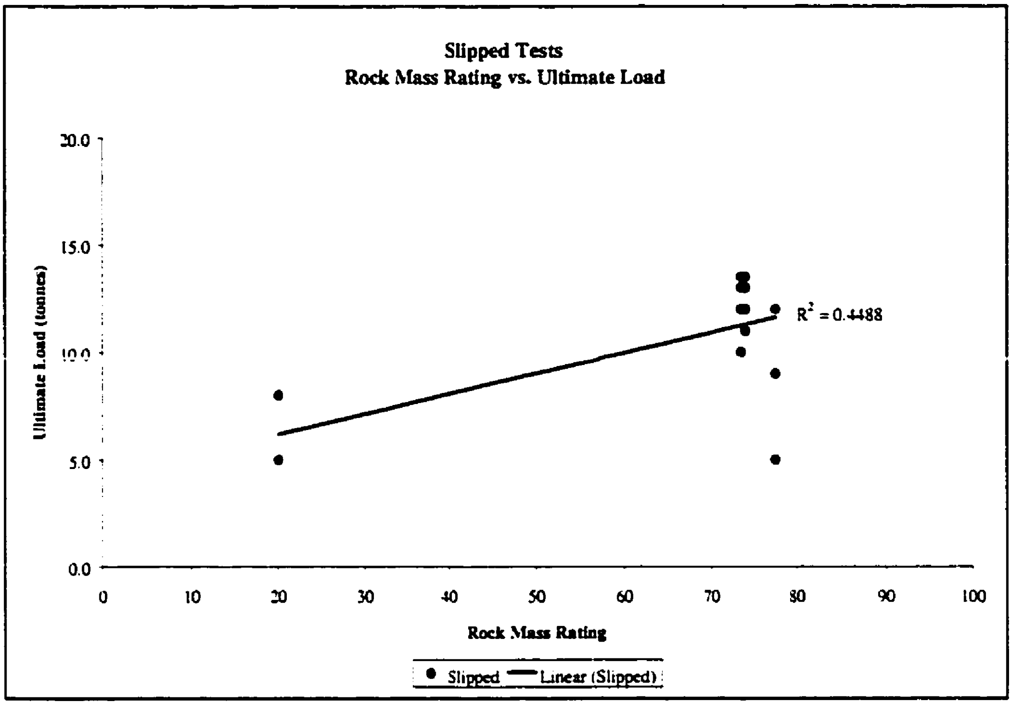

FIGURE 2-62: ROCK MASS RATING VS. ULTIMATE LOAD FOR SLIPPED TESTS

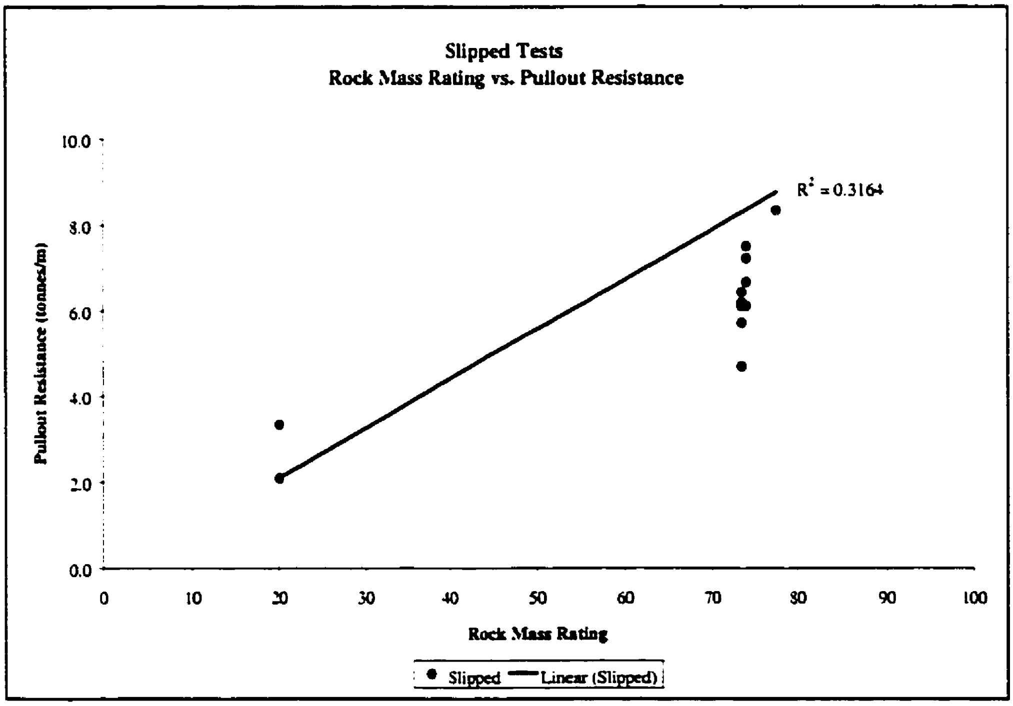

FIGURE 2-63: ROCK MASS RATING VS. PULLOUT RESISTANCE FOR SLIPPED TESTS

2.10.5 Rock Quality Designation

Another factor in determining the rock mass classification is the Rock Quality Designation (RQD). RQD was recorded in a total of 56 of the total 275 pull test records, or 20% of the pull tests records. 22 were slipped test results, 24 were nondestructive test results and 10 were broken test results. A statistical analysis was conducted on the pull tests data for the ultimate load and for the pullout resistance for each of the test types and for all the pull tests as a whole set. The results are presented in Table 2-28.

TABLE 2-28: SUMMARY STATISTICS FOR ROCK QUALITY DESIGNATION FOR ALL TEST TYPES

	All Tests		Slipped Tests		Nondestructive Tests		Broken Tests	
	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)
No. of Tests	56		22		24		10	
Mean	11.98	5.39	12.45	5.97	10.98	4.53	13.35	6.18
Standard Deviation	1.67	1.17	1.75	0.79	1.06	1.11	1.32	0.57

The mean ultimate load for the broken tests is 13.35 tonnes with a standard deviation of 1.32 tonnes, well above the suggested 10 tonnes. The mean ultimate load for the slipped tests was 12.45 tonnes with a standard deviation of 1.75 tonnes, also above the suggested 10 tonnes. The pull test results were plotted graphically. Linear trend lines were fitted through the data for each of the test types. R^2 values were calculated for each of the fitted trend lines. The results for the influence of RQD on ultimate load are shown in Figure 2-64 and for pullout resistance in Figure 2-65. In the interest of clarity, Figures 2-66 and 2-67 are the results for slipped tests alone.

Broken and Nondestructive Tests

The trend line for broken tests for the influence of RQD on the ultimate load is horizontal indicating that RQD has little influence on the breaking load of the bolt. The same result is found in the pull out resistance graph, Figure 2-65. The correlation coefficients (R^2), were quite low for both the ultimate load and for the pullout resistance trend lines which confirmed this result. Of course, there were also only 10 pieces of data in the data set, which is not enough to obtain any sort of meaningful result. The results for the nondestructive tests are overwhelming dependent upon the tester. The results for these tests are provided as a minimum value that these bolts maintained without slipping or breaking.

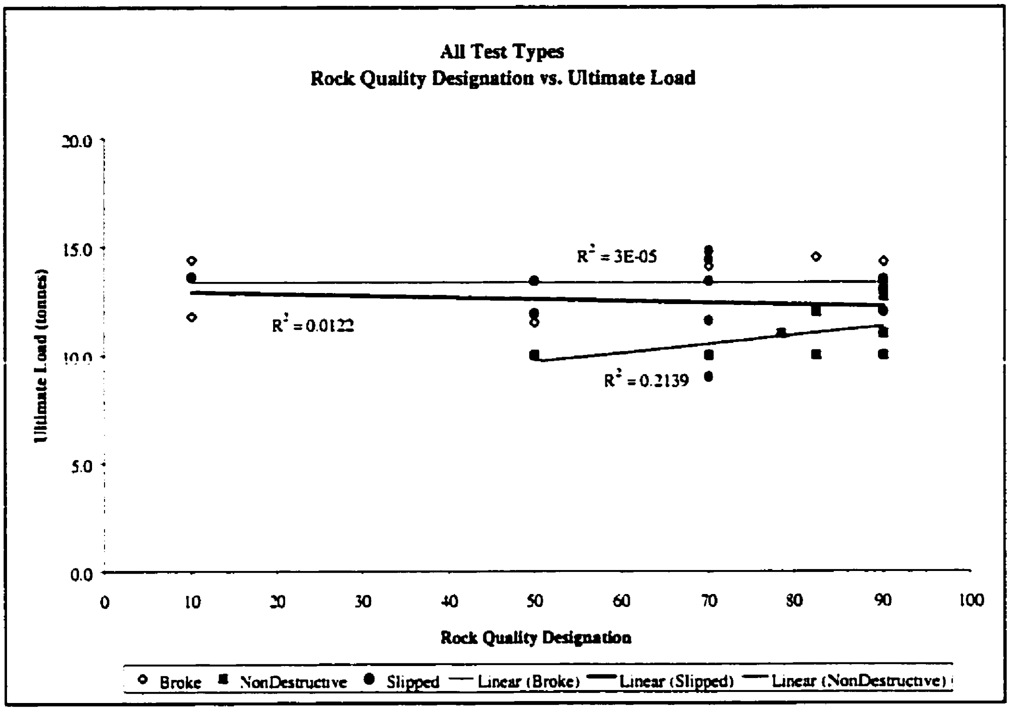

FIGURE 2-64: ROCK QUALITY DESIGNATION VS. ULTIMATE LOAD FOR ALL TEST TYPES

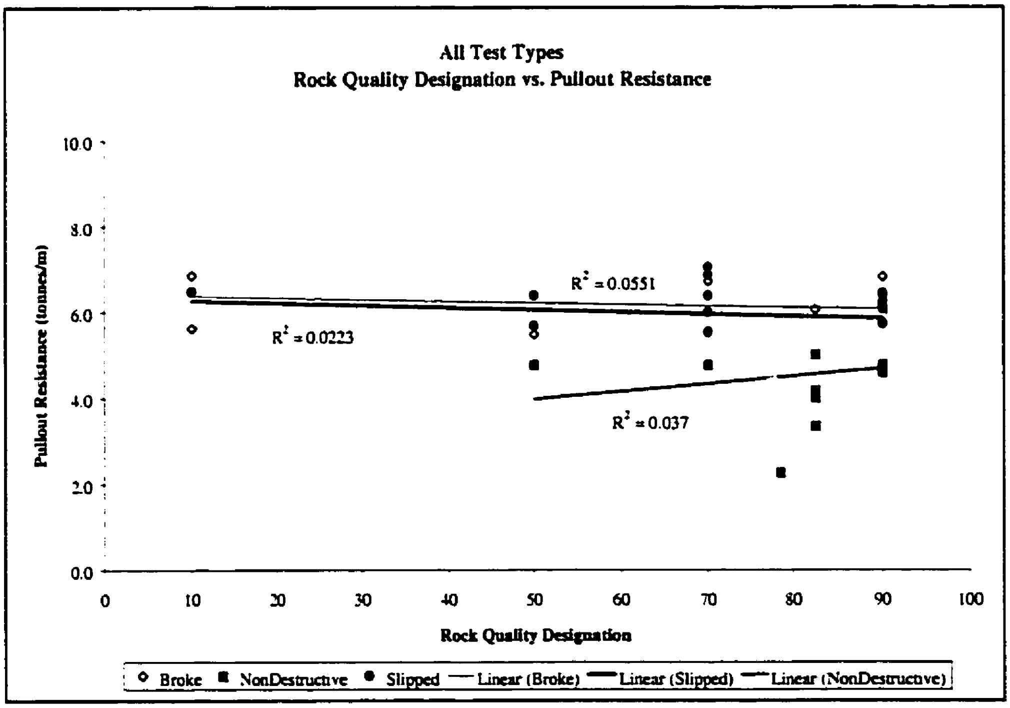

FIGURE 2-65: ROCK QUALITY DESIGNATION VS. PULLOUT RESISTANCE FOR ALL TEST TYPES

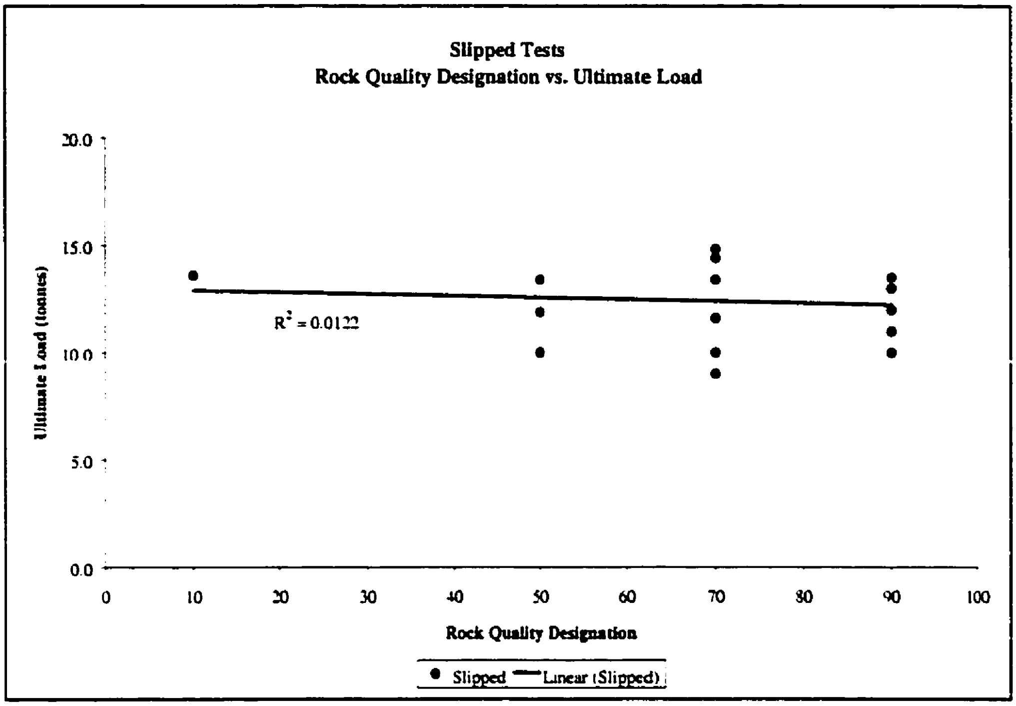

FIGURE 2-67: ROCK QUALITY DESIGNATION VS. ULTIMATE LOAD FOR SLIPPED TESTS

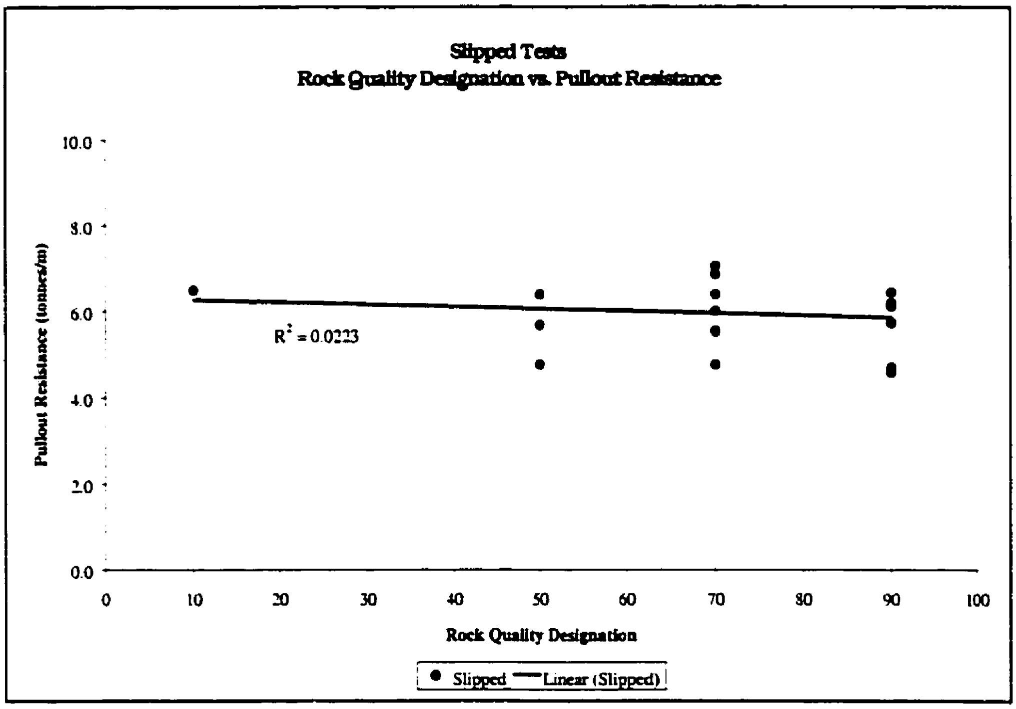

FIGURE 2-68: ROCK QUALITY DESIGNATION VS. PULLOUT RESISTANCE FOR SLIPPED TESTS

Slipped Tests

The trend line for slipped tests for the influence of RQD on the ultimate load is horizontal indicating that RQD has little influence on the slip load of the bolt. The same result is found in the pull out resistance graph, Figure 2-67. The correlation coefficients, R^2 were quite low for both the ultimate load and for the pullout resistance trend lines confirming this result. Again, there were very few pieces of data in the data set, only 22, which is not enough to obtain a meaningful result. There is no observable trend in the tests that failed below the manufacturer's suggested minimum of 10 tonnes. The failed tests are evenly distributed among the different RQD values.

Conclusions

The pull test data available indicates that the RQD has little influence on either the breaking load or the slip load of the bolt. However, there is very little data and more data is required to confirm this result.

2.10.6 Lithology

One of the factors that was found to affect the performance of the Split Set bolt was the type of rock in which the bolt was installed. Information regarding rock type was provided in 159 of the 304 tests, (48% of the total tests). In order to determine what influence the type of rock might have on the performance of the Swellex bolt, the different lithologies had to be grouped together in some classification scheme. For the purposes of classifying the rock types in this set of pull test records, the Terzaghi classification system (1946) was used with some modifications. This is the same classification system that was used by Tomory[18] in his analysis of the performance of Split Set bolts. The rock types were divided into four broad categories which are based on physical characteristics which control the behaviour of the rock mass.

The categories are listed briefly below:

Category	RMR Range	Type
Competent	60 – 80	Crystalline, or hard sedimentary
Laminated	25 – 65	Crystalline, or metasedimentary
Altered, Weathered, Broken	0 – 50	Weathered, shear zones, ore, cemented gravel
Soft Rocks	20 – 60	Extremely weathered, weakly cemented clay, talc, evaporites

The data was separated into these categories based on the information provided. A total 159 records contained information on the rock type, but only 123 could be classified into the categories above, based on the information provided for lithology and, where provided, the UCS and RMR. Some records contained information regarding lithologies which could not be classified into the categories shown above based on the given information alone. Summary statistics were calculated for each of the rock type categories for all tests types grouped together (i.e. slipped, broken and nondestructive tests grouped together), (Table 2-29) and for the slipped tests only (Table 2-30). There was insufficient information to segregate the data by broken and nondestructive tests.

TABLE 2-29: SUMMARY STATISTICS FOR ROCK TYPE FOR ALL TEST TYPES

	Competent		Soft		Laminated		Altered	
	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)
No. of Tests	82		24		9		8	
Mean	12.35	4.19	10.91	6.16	8.72	6.44	10.81	3.53
Standard Deviation	5.74	2.71	3.11	1.15	5.11	1.93	4.18	1.61

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[18] Tomory, P., Performance of Split Set Friction Stabilizer Bolts, University of Toronto, 1997.

TABLE 2-30: SUMMARY STATISTICS FOR ROCK TYPE FOR SLIPPED TESTS

	Competent		Soft		Laminated		Altered	
	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)	Load (tonnes)	Resistance (tonnes/m)
No. of Tests	42		12		6		3	
Mean	13.27	6.52	9.73	6.38	6.21	6.41	14.17	3.87
Standard Deviation	5.56	3.45	3.72	2.56	4.32	2.42	2.47	0.67

The competent rocks performed better than the other rock types, with a mean ultimate load of 12.35 tonnes and a standard deviation of 5.74 tonnes for all Standard Swellex (Table 2-29). The results for competent rock for slipped-tests resulted a mean ultimate load of 13.27 tonnes and a standard deviation of 5.56 tonnes (Table 2-30). The bolts installed in the soft rocks were the second best performers. It is difficult to determine in which category the bolt performed better after that point, due to the lack of data. Histograms were also generated for each of these categories for all tests grouped together. The results are presented in Figure 2-69 through Figure 2-72.

FIGURE 2-69: ALL TESTS – COMPETENT ROCKS

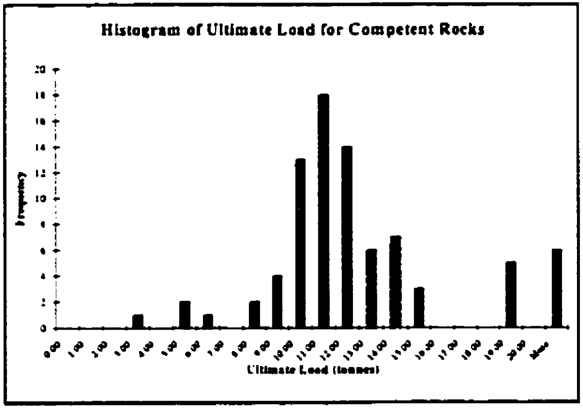


FIGURE 2-70: ALL TESTS – SOFT ROCKS

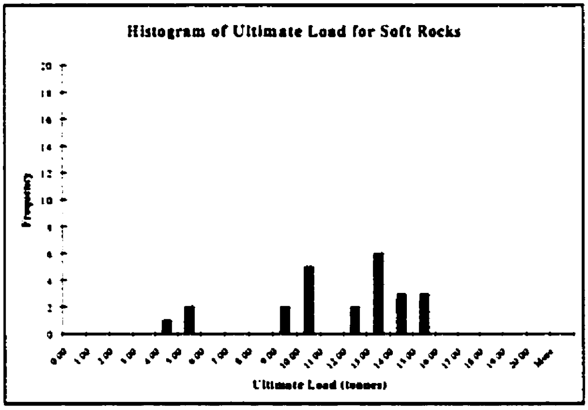


FIGURE 2-71: ALL TESTS – LAMINATED ROCKS

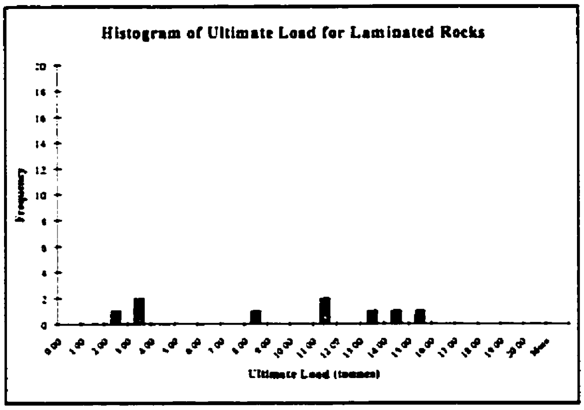
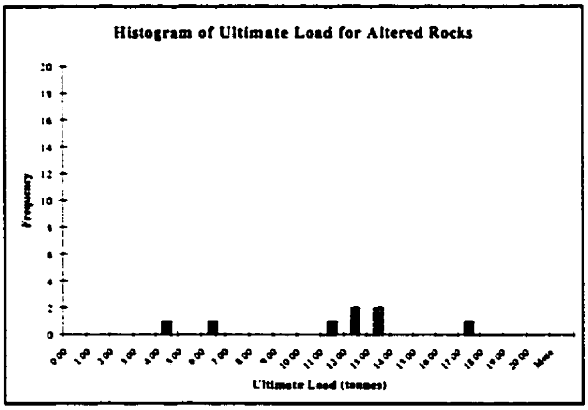


FIGURE 2-72: ALL TESTS – ALTERED ROCKS



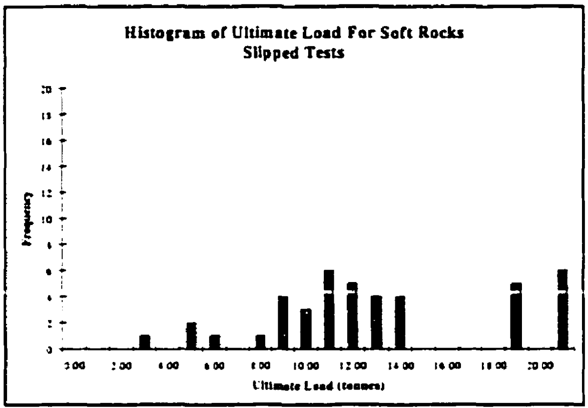


FIGURE 2-73: SLIPPED TESTS – COMPETENT ROCKS

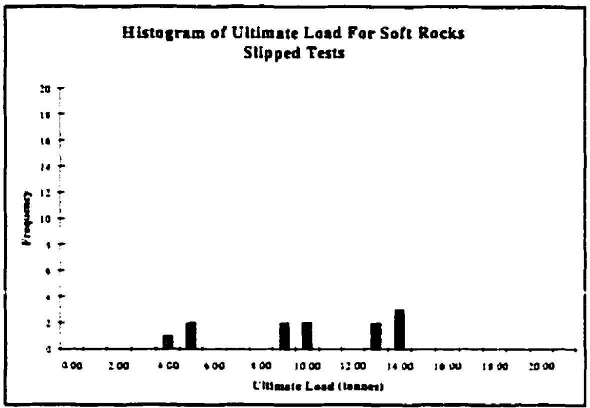


FIGURE 2-74: SLIPPED TESTS – SOFT ROCKS

As well, the histogram of the ultimate load was plotted for slipped tests only for the competent and for the soft rock types. There was insufficient data to generate these plots for the altered and laminated rock types. The results are presented in Figures 2-73 and Figure 2-74. It is difficult to make any comments about the observed trends in the data for rock type, as there is insufficient data in most of the categories to draw any conclusion. The only category that has a sufficient amount of data is the competent rock category. Data in only one category is not sufficient to identify trends by rock type.

2.11 SUMMARY OF THE STATISTICAL ANALYSIS

The results of the statistical analysis of the various parameters are summarized in Table 2-31.

TABLE 2-31: SUMMARY OF STATISTICAL ANALYSIS OF THE INFLUENCE OF VARIOUS PARAMETERS ON THE ULTIMATE LOAD OF THE SWELLEX BOLT.

Parameters	Standard Swellex Bolts							
	Slipped Tests, Ultimate Load				Broken Tests, Ultimate Load			
	Number of Tests	R^2	Trend line	Comments	Number of Tests	R^2	Trend line	Comments
Bolt & Installation Parameters								
Length of Bolt	148	0.1224	positive linear	some influence	41	0.0011	horizontal linear	no influence
Drilled Hole Diameter	129	0.0317	2nd order polynomial	some influence	29	0.0880	horizontal, 2nd order, polynomial	more data required
Mean values	4	0.3320	2nd order polynomial	strong influence	-	-	-	-
Drilled Bit Diameter	23	0.1690	2nd order polynomial	some influence	10	0.0825	horizontal, 2nd order polynomial	more data required
Mean values	4	0.5542	2nd order polynomial	strong influence	-	-	-	-
Pump Pressure	68	0.4112	positive, linear	**strong influence**	23	0.0001	horizontal linear	no influence
Mean values	4	0.9478	positive, linear	strong influence	-	-	-	-
Time Parameters								
Corrosion Level	35	0.3688	2nd order polynomial	**strong influence**	11	0.3225	2nd order polynomial	**strong influence**
Mean values	4	0.9973	2nd order polynomial	strong influence	-	-	-	-
Test Date	109	0.0066	linear horizontal	no influence	21	0.0106	linear horizontal	no influence
Installation Date	50	0.0052	linear horizontal	no influence	15	0.4720	positive, linear	**strong influence**
Residence Time	50	0.3116	negative, linear	moderate influence	15	0.4883	negative, linear	**strong influence**
Ground Conditions								
Elastic Modulus	11	0.3981	negative, linear	moderate influence	5	0.2411	linear horizontal	no influence, more data required
UCS	34	0.4183	logarithmic	**strong influence**	15	0.3503	linear horizontal	more data required
Water Level	33	0.0126	linear horizontal	more data required	9	0.1018	linear horizontal	more data required
RMR	15	0.4488	positive, linear	more data required	6	0.0211	linear horizontal	more data required
RQD	22	0.0122	linear horizontal	more data required	10	<0.0001	linear horizontal	more data required
Lithology	123	-	-	more data required	-	-	-	-

The parameters which showed some influence on the ultimate bearing capacity or the breaking capacity of the bolt are shaded in Table 2-31.

Broken Tests

The parameters which were found to have an appreciable influence on the ultimate load of the bolt in broken tests were:

- ☐ level of corrosion
- ☐ installation date
- ☐ residence time

In the case of corrosion and residence time, an increase in each respectively, results in a decrease in ultimate bearing capacity. For installation date, the earlier the installation date, the lower the bearing capacity of the bolt. This trend is most likely the result of the underlying influence of the age of the bolt, as most of the test data is from the last few years. The installation date of the bolt, on the other hand, is well distributed over the past 12 years. This trend may also be the result of improved installation practices over time, or an improvement in the bolt manufacturing itself. Water level did not show any influence on the breaking strength of the bolt. However, as there were only 9 records for water level and broken tests, more data is required to validate this result. More data would probably show that water level does have some influence on the breaking strength of the bolt, as the presence of water is one of the factors in the corrosion process. Since corrosion has an influence, it stands to reason that water level should have an influence as well.

Slipped Tests

The parameters which showed some influence on the ultimate bearing capacity of the bolt, or the slip load, were:

- ☐ length of the bolt
- ☐ drilled hole diameter
- ☐ drill bit diameter
- ☐ pump pressure
- ☐ corrosion level
- ☐ residence time
- ☐ elastic modulus
- ☐ UCS

These parameters are discussed in greater detail in Section 3. The parameters which have been ruled out as having an influence on the ultimate bearing capacity of the bolt, based on the information available, are: RMR, RQD, the test date and the installation date. The rest of the parameters generally required more data to be excluded from having an effect on the ultimate bearing capacity of the bolt.

Another important observation from Table 2-31 is the lack of information with respect to many of the parameters. Clearly, an increase in the amount of information that is recorded when conducting a pull test is required. Standardization of the data recorded is also required in order to easily interpret and analyse the data. Particularly, a standardization in the terminology used to describe the results of the test (i.e., nondestructive, broke, or slipped tests), and in the terminology used for qualitative data (e.g. level of corrosion), is required. A quantitative method of assessing water level and level of corrosion is the preferred alternative but would be difficult. Section 4 and 5 deal with these issues in further detail.

3

DISCUSSION OF STATISTICAL RESULTS AND DESIGN RECOMMENDATIONS

3.0 INTRODUCTION

The purpose of this section is to summarize the results of the statistical analysis and to validate or exclude the influence of the parameters. The purpose is also to develop design considerations based on the results of this investigation. A summary of results of the statistical analysis on the pull test data is provided in Table 3-1. Only those parameters which were found to have an influence on the performance of the Swellex bolt are included in Table 3-1.

TABLE 3-1: SUMMARY OF PARAMETERS WHICH INFLUENCE THE PERFORMANCE OF SWELLEX BOLTS

Parameters	Slipped Tests, Ultimate Load				Broken Tests, Ultimate Load			
	Number of Tests	R^2	Trend line	Comments	Number of Tests	R^2	Trend line	Comments
Bolt & Installation Parameters								
Length of Bolt	148	0.1224	positive linear	some influence				
Drilled Hole Diameter	129	0.0317	2^{nd} order polynomial	some influence				
Mean values	4	0.3320	2^{nd} order polynomial	strong influence				
Drilled Bit Diameter	23	0.1690	2^{nd} order polynomial	some influence				
Mean values	4	0.5542	2^{nd} order polynomial	strong influence				
Pump Pressure	68	0.4112	positive, linear	strong influence				
Mean values	4	0.9478	positive, linear	strong influence				
Time Parameters								
Corrosion Level	35	0.3688	2^{nd} order polynomial	strong influence	11	0.3225	2^{nd} order polynomial	strong influence
Mean values	4	0.9973	2^{nd} order polynomial	strong influence				
Installation Date					15	0.4720	positive, linear	strong influence
Residence Time	50	0.3116	negative, linear	moderate influence	15	0.4883	negative, linear	strong influence
Ground Conditions								
Elastic Modulus	11	0.3981	negative, linear	moderate influence				
UCS	34	0.4183	logarithmic	strong influence				

3.1 BROKEN TEST RESULTS

The data shown in Table 3-1 indicates that the parameters which were found to have an influence on the breaking strength of the bolt were the corrosion level, the installation date and the residence time. There were 11 broken tests in which corrosion level was recorded. The trend line in the ultimate load chart had a correlation coefficient of $R^2 = 0.3325$. However, it should be noted that this correlation is subjective since the x-axis of the chart is qualitative. The trend line which was fitted through the data was a second order polynomial trend line. The trend line indicated that an increase in corrosion resulted in a decrease in the ultimate bearing capacity of the bolt. The installation date and the residence time showed essentially the same trend; increased residence time and older installation dates, increased the tendency of the bolts to break at a lower ultimate load. There were only 15 bolts in which residence time and installation date were recorded. In order to investigate whether the results of the installation date were the results of an underlying influence of the residence time, the data was compared for these two parameters. In the comparison, the older installation dates had corresponding longer residence times. The higher corrosion levels also corresponded to the longer residence times. Table 3-2 contains the corrosion, residence time and installation date information for broken tests.

TABLE 3-2: CORROSION, INSTALLATION DATE, RESIDENCE TIME AND ULTIMATE LOAD INFORMATION FOR BROKEN TESTS

Test Type	Corrosion Level	Installation Date	Residence Time (days)	Load (tonnes)
Broke	Moderate	19-Mar-97	110	14.10
Broke	Surficial	19-Jun-94	183	12.50
Broke	Surficial	19-Sep-93	456	12.00
Broke	Very	1-Sep-95	677	11.50
Broke	Surficial	12-Aug-96	730	8.00
Broke	Moderate	19-Dec-88	2191	8.50
Broke	Moderate	19-Dec-88	2191	6.50
Broke	Moderate	19-Dec-88	2191	5.50
Broke	Very	19-Dec-88	2191	3.50
Broke	Surficial	15-Jan-88	3288	8.60
Broke	Surficial	15-Jan-88	3288	7.50

An examination of the data in Table 3-2 indicates that the overriding influence on the breaking capacity of the bolt is the corrosion level in combination with the exposure time (residence time of the bolt). The installation date does not have an independent influence on the performance of the bolt. It is difficult to further model or make recommendations based on corrosion levels as this is not an easily quantified parameter. Additionally, this parameter is not easily controlled or manipulated, so design recommendations based on corrosion would be of limited usefulness.

3.2 SLIPPED TEST RESULTS

A number of parameters were analysed statistically in order to assess their level of influence on the slip load of the bolt in the previous section (Section 2). Some of these factors were excluded from having an influence while others required more data to confirm or exclude. There were a number of parameters which were found to have an influence on the slip load of the bolt. In order to assess the level of influence and the validity of these findings a number of investigations were conducted on the resulting parameters. Comparison charts were plotted with these parameters in order to clarify the plots. The finite element modelling program Phase^2 was used to simulate the installation process in order to determine the relationship between the parameter and the ultimate load of the bolt. A sensitivity analysis using the relationship between the parameters and the equilibrium stress acting on the bolt was also conducted, which resulted in an influence chart.

3.2.1 Discussion of Parameters

The statistical analysis in the previous section indicated that the corrosion level, the residence time, the UCS, the elastic modulus, the pump pressure, the drilled hole diameter and the drill bit diameter have an influence on the slip load of the bolt. Additionally, the length of the bolt was also found to have an influence. However, the length-ultimate load relationship is too complex to be modelled or to be determined with the given information. Therefore, the influence of length has been excluded from further analysis.

Table 3-3 is the pull test information for tests in which information for corrosion level and residence time was recorded. There was no observable trend in the information. It is difficult to further analyse the influence of residence time and corrosion level as an underlying influence on the results of any of the other parameters as there were only 2 records which contained information regarding corrosion and residence time that also contained information for UCS, drilled hole diameter and elastic modulus. There were no records for which there was information for corrosion level, residence time and pump pressure. Because of a lack of overlap in the data for these parameters, corrosion level, and residence time were excluded from further analysis. These parameters are not parameters that are in any way controllable, or in the case of corrosion, easily quantified. Therefore, it would be difficult to make any specific recommendations as to these parameters in relation to design considerations, except to say that more data is required to quantify the exact relationship between corrosion and slip load. Also excluded from further analysis is the drill bit diameter, because it is in fact a reflection of the underlying influence of the drilled hole diameter.

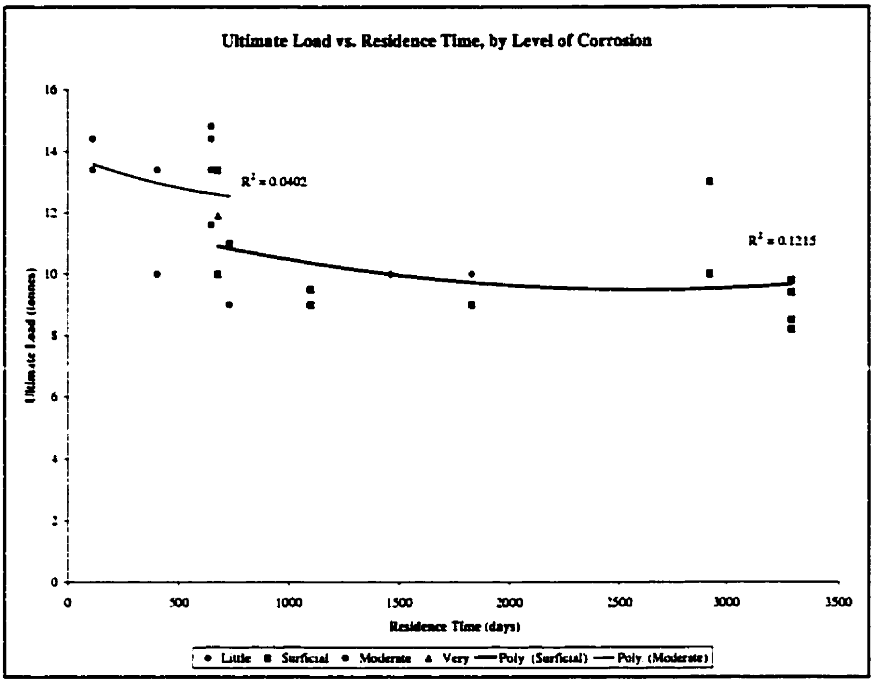


FIGURE 3-1: ULTIMATE LOAD VS. RESIDENCE TIME BY LEVEL OF CORROSION FOR SLIPPED TESTS

TABLE 3-3: ULTIMATE LOAD VS. RESIDENCE TIME BY LEVEL OF CORROSION

Test Type	Corrosion	Residence Time (days)	Drilled Hole Diameter (mm)	Pump Pressure (MPa)	UCS (MPa)	Elastic Modulus (GPa)	Load (tonnes)
Slipped	Little	1461					10.00
Slipped	Little	1827					10.00
Slipped	Surficial	676					10.00
Slipped	Surficial	676					13.40
Slipped	Surficial	730					11.00
Slipped	Surficial	1096					9.00
Slipped	Surficial	1096					9.50
Slipped	Surficial	1827					9.00
Slipped	Surficial	2922	38		112	14-45	10.00
Slipped	Surficial	2922	38		112	14-45	13.00
Slipped	Surficial	3288					9.40
Slipped	Surficial	3288					8.20
Slipped	Surficial	3288					8.50
Slipped	Surficial	3288					9.80
Slipped	Moderate	110					14.40
Slipped	Moderate	110					13.40
Slipped	Moderate	401					13.40
Slipped	Moderate	401					10.00
Slipped	Moderate	647					14.40
Slipped	Moderate	647					14.40
Slipped	Moderate	647					11.60
Slipped	Moderate	647					13.40
Slipped	Moderate	647					14.80
Slipped	Moderate	730					9.00
Slipped	Very	677					11.90
Slipped	Very	677					10.00

The elimination of corrosion level, residence time, and length from further analysis leaves the final four parameters to be analysed: pump pressure, drilled hole diameter, uniaxial compressive strength and elastic modulus.

Pump Pressure

From Table 3-1, the relationship for pump pressure was found to be linear with a correlation coefficient of $R^2 = 0.4112$. The slope of the trend line was positive which indicated that an increase in pump pressure resulted in an increase in slip load.

Drilled Hole Diameter

The relationship for drilled hole diameter was found to be a second-order polynomial with a correlation coefficient of $R^2 = 0.0317$, a rather low value, attributable to the scatter within the discrete intervals of drilled hole diameter. This scatter is probably the result of other parameters. In order to clarify this plot, the mean value for the each of the intervals was plotted against the mean ultimate load for that interval. The same second-order polynomial trend line was fitted to the data and the correlation coefficient was much higher, $R^2 = 0.3320$. The inflection of the curve indicated that the ultimate load of the bolt increased within the manufacturer's recommended drilled hole diameter range (32 to 39 mm) and decreased outside that range.

Elastic Modulus

The trend line for the influence of elastic modulus of the rock in which the bolt was installed was linear. The slope of the line was negative indicating that an increase in elastic modulus resulted in a decrease in ultimate load of the bolt. The correlation coefficient of the trend line was $R^2 = 0.3981$, rather high, compared to the other parameters. However there were only 11 data points for elastic modulus.

Uniaxial Compressive Strength

The trend line for the influence of the UCS of the rock in which the bolt is installed on the ultimate load of the bolt appears to be logarithmic, with a correlation coefficient of 0.4183, indicating a strong influence. However, the relationship is probably closer to being bi-linear, with a curved trend line in the 0 to 40 MPa range and a linear, near horizontal relationship for the over 40 MPa range. There were 34 data points in which the UCS of the rock was recorded. The trend line indicated that the lower UCS rocks, resulted in a lower ultimate load of the bolt. Beyond 50 MPa, the UCS had little influence on the slip load of the bolt.

3.2.2 Combinations of Parameters

In order to clarify the scatter in the drilled hole diameter charts and the pump charts, the influence of the remaining four parameters, drilled hole diameter, pump pressure, UCS and elastic modulus on the ultimate load was plotted as a function of 2 parameters at a time using bubble charts. This resulted in five combinations: pump pressure and drilled hole diameters, drilled hole diameter and UCS, drilled hole diameter and elastic modulus, pump pressure and UCS, pump pressure and elastic modulus. The size of the bubble represents the ultimate load. The chart for pump pressure vs. elastic modulus contained insufficient information to be plotted. The remaining four charts are shown in Figure 3-2 to Figure 3-5.

In Figure 3-2, the Ultimate Load was plotted vs. Drilled Hole Diameter and Elastic Modulus. There were a total of 11 pull test records that contained information for both of these parameters. Separating the results for drilled hole diameter by the elastic modulus did not clarify the plot and no further resulting trends were observed. This is likely the result of a lack of data.

In Figure 3-3, the Ultimate Load was plotted vs. Drilled Hole Diameter and Pump Pressure. There were a total of 58 pull test records that contained information for both of these parameters. Separating the results for drilled hole diameter by the pump pressure did show that pump pressures below 25 MPa resulted in poor ultimate loads for all drilled hole diameters.

In Figure 3-4, the Ultimate Load was plotted vs. Drilled Hole Diameter and Uniaxial Compressive Strength. There were a total of 36 pull test records that contained information for both of these parameters. Separating the results for drilled hole diameter by the UCS showed that bolts installed in rock with a UCS of less than 30 MPa resulted in poor ultimate loads for all drilled hole diameters. Pull test results for bolts installed in rock with UCS values greater than 30 MPa, showed that the UCS had little influence on the ultimate load.

In Figure 3-5, the Ultimate Load was plotted vs. Pump Pressure vs. Uniaxial Compressive Strength. There were a total of 21 pull test records that contained information for both of these parameters. It should be noted that many points were overlaid. For example, the data point plotted at 6 MPa UCS and 22 MPa pump pressure is actually 6 points with ultimate loads ranging from 4.30 tonnes to 8.20 tonnes. The plot showed that bolts installed with pump pressures below 27 MPa performed poorly for all UCS values and bolts in rock with UCS values less than the pump pressure performed poorly.

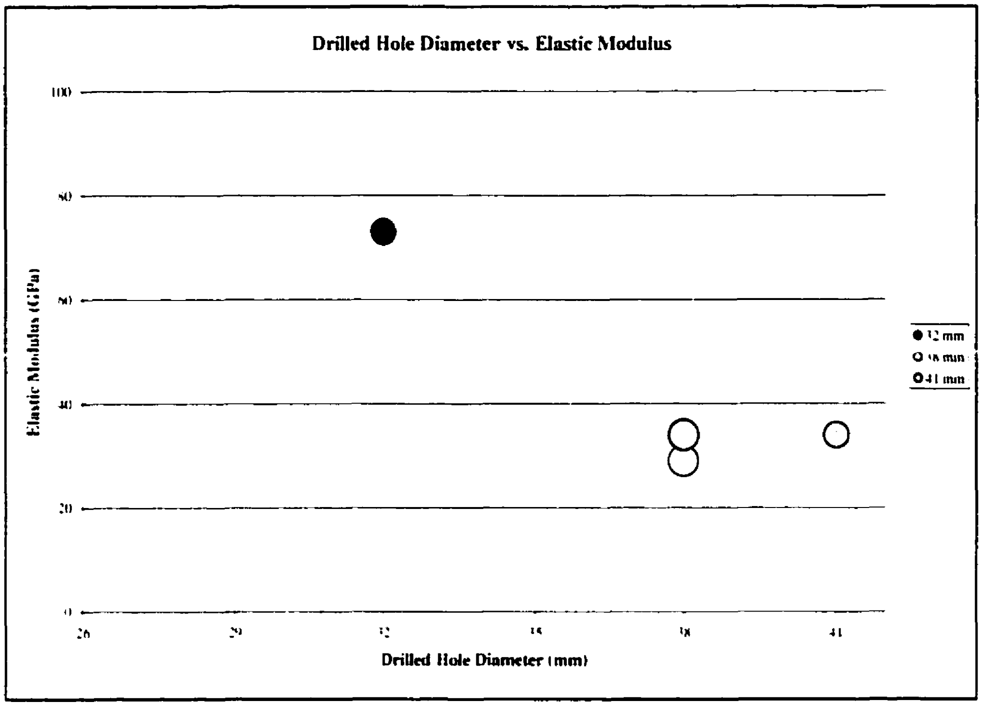


FIGURE 3-2: DRILLED HOLE DIAMETER VS. ELASTIC MODULUS FOR SLIPPED TESTS

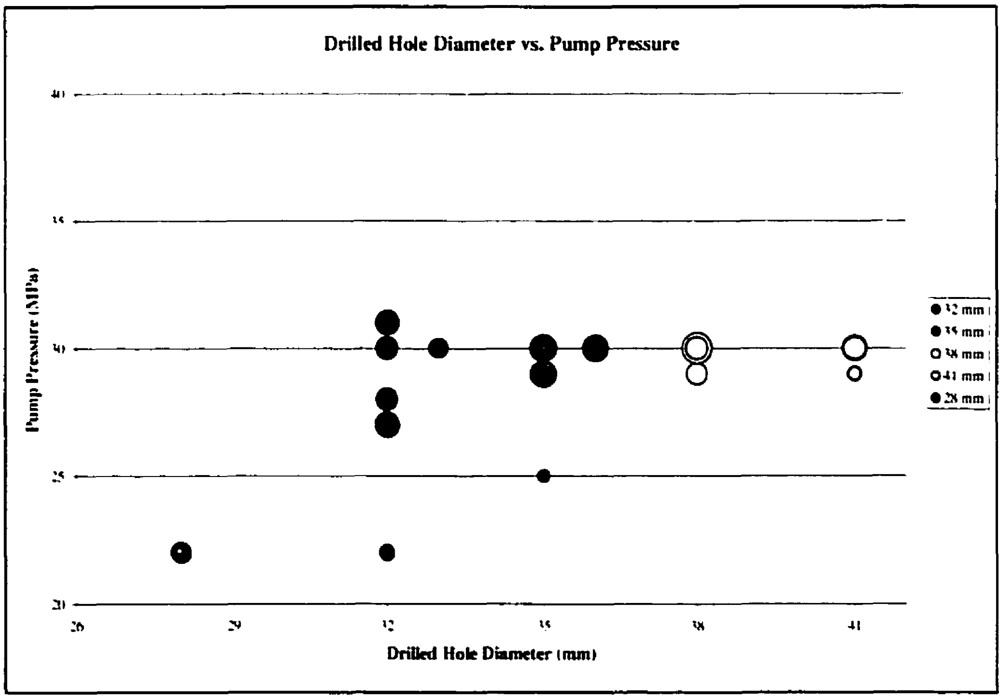


FIGURE 3-3: DRILLED HOLE DIAMETER VS. PUMP PRESSURE FOR SLIPPED TESTS

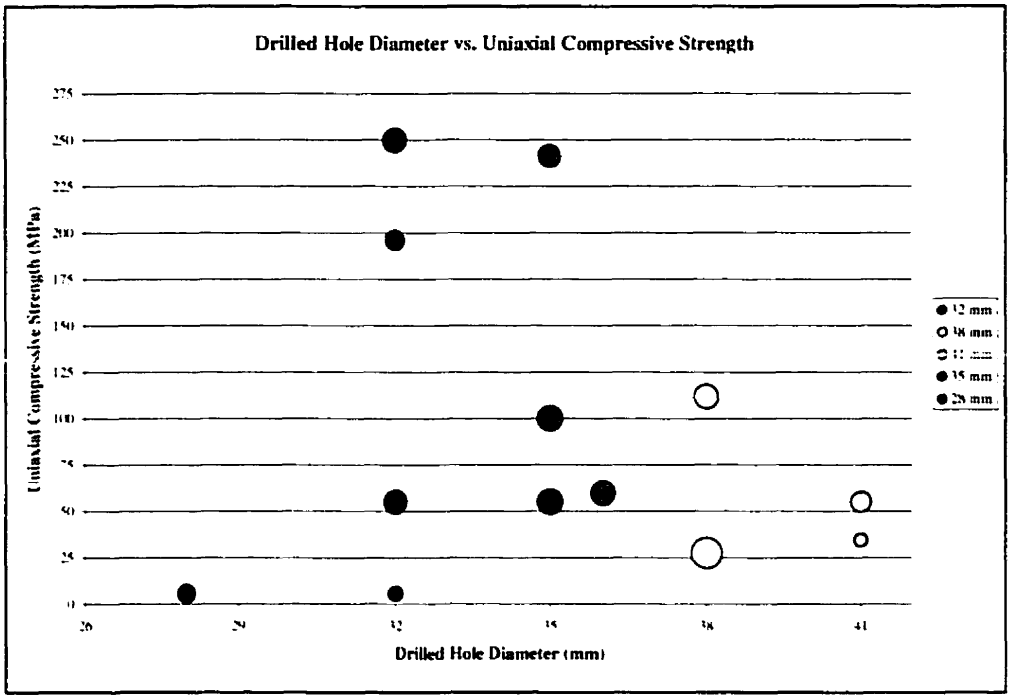


FIGURE 3-4: DRILLED HOLE DIAMETER VS. UNIAXIAL COMPRESSIVE STRENGTH FOR SLIPPED TESTS

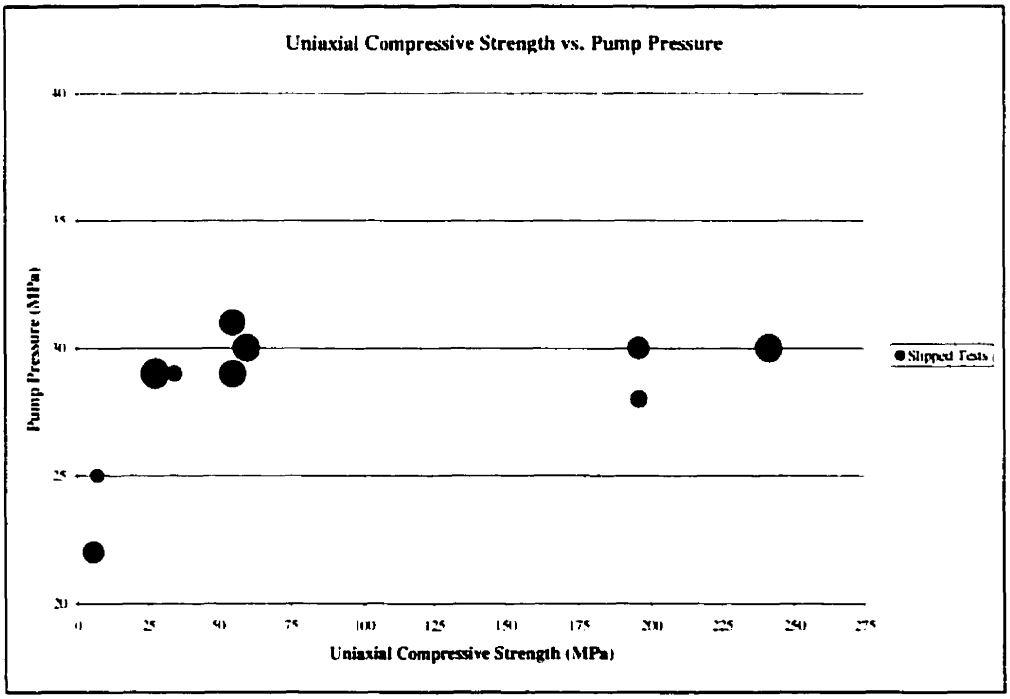


FIGURE 3-5: UNIAXIAL COMPRESSIVE STRENGTH VS. PUMP PRESSURE FOR SLIPPED TESTS

3.2.3 Sensitivity Analysis Using Phase^2 Models

In order to determine the relationship between these four parameters and the ultimate load of the Swellex bolt (due to of a lack of data for these parameters) it was necessary to simulate data where there was none. The installation process for a Swellex bolt was modelled using Phase^2, a finite element modelling program. A three-stage model was used, similar to the three stages of the installation process for a Swellex bolt. In the first stage, a 38 mm hole was excavated (the size of the borehole in which a Swellex bolt is installed). In the second stage, a liner with 2 mm thickness and with the same properties as a Swellex bolt was installed in the excavation and an internal pressure of 30 MPa was applied (simulating the water pressure which inflates the bolt). In the final stage the 30 MPa internal pressure is removed (simulating the release of the water pressure). The models were run elastically for the differing values of drilled hole diameter, pump pressure and elastic modulus and plastically for the different values of UCS. A uniform field stress of 50 MPa was used.

Each of the parameters, excavation diameter, internal pressure, UCS and elastic modulus of the rock, was successively varied over a range (a model was run for each value) while the other three parameters remained fixed. The internal pressure (pump pressure) values used were 10 to 50 MPa, in 5 MPa increments, while the hole diameter was fixed at 38 mm, the UCS at 50 MPa and the elastic modulus at 70 GPa. The drilled hole diameter values used were 32, 35 and 38 mm, while pump pressure was fixed at 30 MPa, the UCS at 50 MPa, and the elastic modulus at 70 GPa. The UCS values used were 10, 20, 30, 40, 50, 60, 80, 100, 125, 150 175 and 200 MPa, while the pump pressure was fixed at 30 MPa, the hole diameter was fixed at 38 mm and the elastic modulus at 70 GPa. Finally, the values for elastic modulus were, 10 to 200 GPa in 10 GPa increments, while the pump pressure was fixed at 30 MPa, the drilled hole diameter was fixed at 38 mm and the UCS at 50 MPa.

The normal (radial) stress acting on the interface between the excavation and the bolt control the mechanical locking force that acts on the bolt which in turn is related to the ultimate load of the bolt. This normal stress acting on the bolt for each of the values of elastic modulus were plotted in a chart shown in Figure 3-6. A trend line was fitted through the data using regression. The results of the sensitivity analysis showed that the relationship for elastic modulus was in fact a power function (inversely proportional), and not a linear relationship as was found from the available data in the statistical analysis of Section 2. For pump pressure, the normal stress on the bolt was plotted for each value of pump pressure. A trend line was fitted through the data using linear regression. The results of the sensitivity analysis confirmed that the relationship between the pump pressure and the

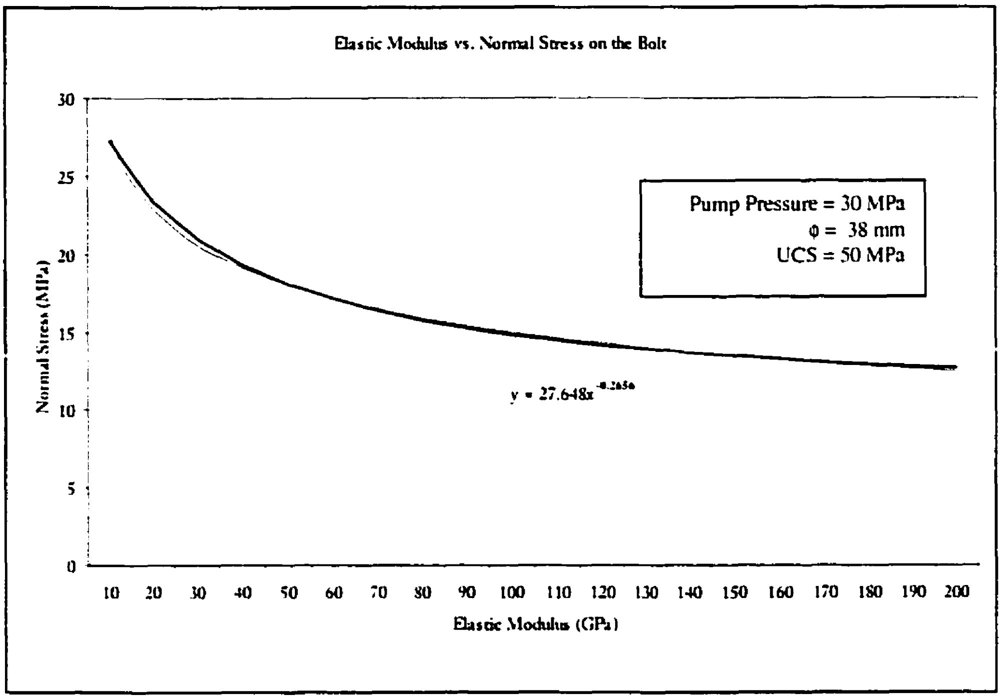


FIGURE 3-6: RESULTS OF SENSITIVITY ANALYSIS ON ELASTIC MODULUS

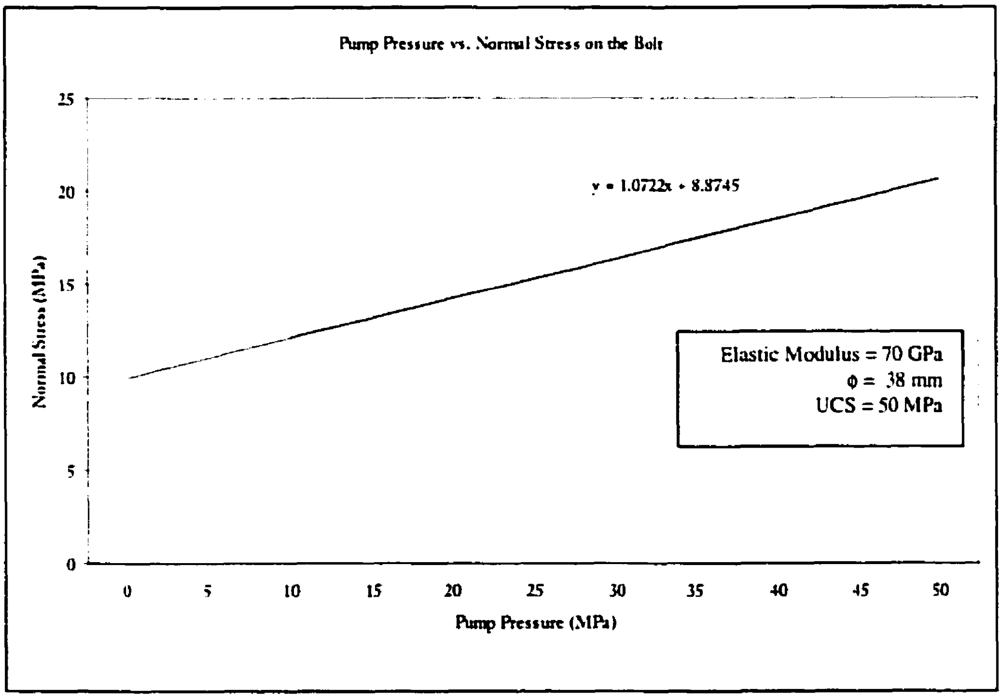


FIGURE 3-7: RESULTS OF SENSITIVITY ANALYSIS ON PUMP PRESSURE

ultimate load of the bolt (which is a function of the clamping stress on the bolt) is linear. The results for the other two parameters were not as clear. The drilled hole diameter showed that the smaller diameters increased the normal stress on the bolt. This result is opposite to the results that were found in the statistical analysis, and opposite to what Atlas Copco Ltd. recommends. The exact process is difficult to model because the liner elements in the Phase^2 model must be attached to the rock elements, and a gap between the two (the fold in the Swellex bolt) cannot be modelled. The Swellex bolt however, is not fully attached, because of the folded portion of a Swellex bolt. The folded Swellex bolt inflates and attains a near circular shape, however a small fold remains even at the recommended 38 mm diameter which changes the stiffness and the stress distribution on the bolt.[19]

The model results for the influence of UCS on the normal stress were also unclear. The model was run plastically, and local crushing of the rock resulted in a non-even distribution of the normal stress on the drill hole boundary, which could not be easily interpreted.

3.2.4 Design Curve for Pump Pressure and Elastic Modulus

The normal stress (the clamping stress which creates the mechanical locking effect in Swellex) acting on the bolt, is a function of the equilibrium pressure between the rock and the bolt. This in turn is a function of the displacement of the rock and the bolt. In order to define some design considerations with respect to the pump pressure and the elastic modulus, a graph was created which compared the normal stress acting on the bolt to the elastic modulus of the rock, for various elastic modulus values at different pump pressures. The formulae for the equations in the spreadsheet were derived from Popov's Mechanics of Materials, for Thin-Walled Cylinders.[20]

The equation for the radial displacement in a thin-walled cylinder with external pressure is:

$$\mu_r = -\frac{1-v^2}{E}\cdot\frac{p_0 r^2}{t}$$

Where:
μ_r is the radial displacement of the bolt (positive radially outwards)
p_0 is the initial pressure
r is the radius (drilled hole diameter)
t is the thickness of the cylinder
E is the elastic modulus of the cylinder

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[19] Wijk, G., and Skogberg, B., The SWELLEX Rock Bolting System, Rock Breaking and Mechanical Excavation, Canadian Institute of Mining and Metallurgy, CIM Special Vol. 30, pp. 106-110.

[20] Popov, E.P., Mechanics of Materials, Thin Walled Cylinders, p. 290

The change in radial displacement of the hole is:

$$\Delta\mu_r = -\frac{p_h}{2G_r}r + \frac{p_{eq}}{2G_r}r$$

Where: p_h is the pressure on the hole (the pump pressure)
p_{eq} is the equilibrium pressure
G_r is the shear modulus of the rock

Equating the radial displacements yields:

$$-\frac{p_h}{2G_r}r + \frac{p_{eq}}{2G_r}r = -\frac{1-\nu_h^2}{E_h}\cdot\frac{p_{eq}r^2}{t_h}$$

Where: ν_h is the Poisson's ratio of the bolt (0.2)
E_h is the elastic modulus of the bolt (210 GPa)
t_h is the thickness of the bolt (0.002 m)

Solving for the equilibrium pressure, the equation reduces to:

$$p_{eq} = \frac{p_h}{1 + 2G_r\cdot\frac{1-\nu_h^2}{E_h}\cdot\frac{r}{t_h}}$$

This equation for the pressure at which the bolt and the rock reach equilibrium was used in a spreadsheet to develop the graph shown in Figure 3-8. This equilibrium pressure is the clamping stress or the normal stress which results from the installation process of the Swellex bolt. The elastic modulus for the rock, E, ($2G_r = E_r/(1+\nu_r)$) was varied over a range of 10 GPa to 200 GPa, for each of the following pump pressures: 25 MPa, 30 MPa, 35 MPa and 40 MPa. The Poisson's ratio of the rock was fixed at 0.2. The drilled hole radius (r) was fixed at 19 mm, which is the manufacturer's recommended radius and the radius at which the Swellex bolt performed the best in the statistical analysis of Section 2. The results of the sensitivity analysis are presented in a design chart shown in Figure 3-8. The elastic modulus used for the bolt was 210 GPa and the Poisson's ratio for the bolt was 0.2. From Figure 3-8, and Table 3-4, the elastic modulus has a significant influence on the normal stress acting on the bolt for rocks with an elastic modulus less than 70 GPa. Elastic modulus has an increasingly diminished influence on Swellex bolts installed in a rock with an elastic modulus greater than 70 GPa. Additionally, an increase in pump pressure of 5 MPa results in an increase in normal stress of approximately 3.75 MPa (at an elastic modulus of 70 GPa).

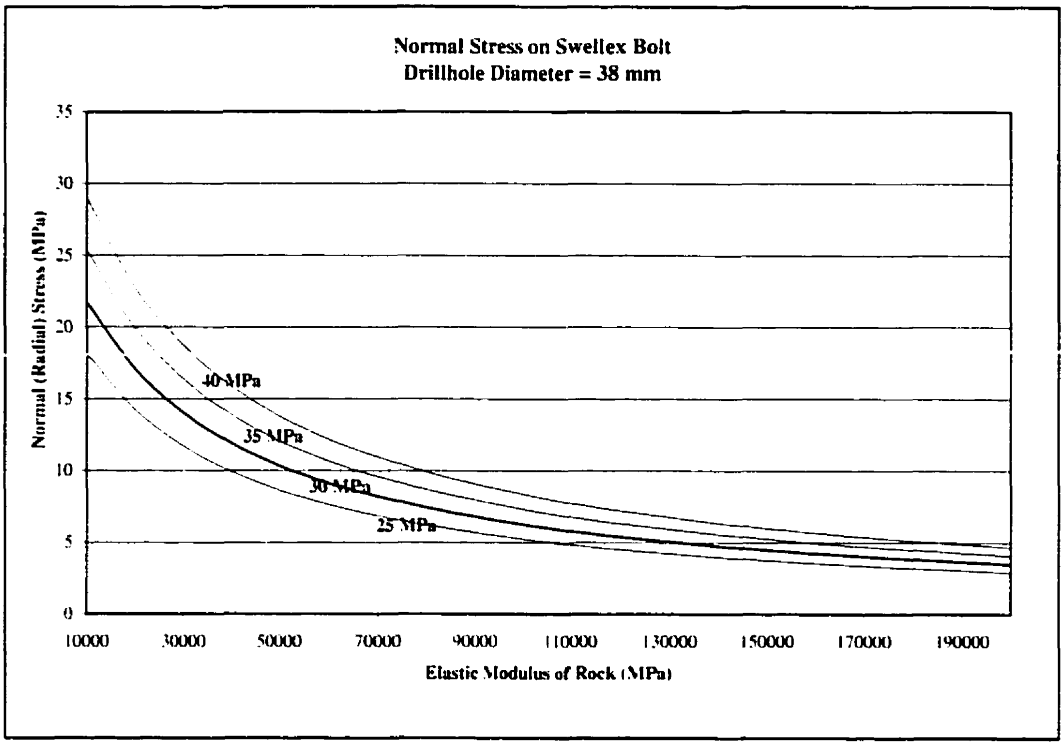

FIGURE 3-8: INFLUENCE OF ELASTIC MODULUS ON THE NORMAL STRESS ON SWELLEX FOR VARIOUS PUMP PRESSURES

TABLE 3-4: NORMAL STRESS ON SWELLEX FOR VARIOUS PUMP PRESSURES

Rock Properties		Pump Pressure			
E_r (MPa)	v_r	25 (MPa)	30 (MPa)	35 (MPa)	40 (MPa)
10000	0.2	18.12	21.74	25.36	28.99
20000	0.2	14.20	17.05	19.89	22.73
30000	0.2	11.68	14.02	16.36	18.69
40000	0.2	9.92	11.90	13.89	15.87
50000	0.2	8.62	10.34	12.07	13.79
60000	0.2	7.62	9.15	10.67	12.20
70000	0.2	6.83	8.20	9.56	10.93
80000	0.2	6.19	7.43	8.66	9.90
90000	0.2	5.66	6.79	7.92	9.05
100000	0.2	5.21	6.25	7.29	8.33
110000	0.2	4.83	5.79	6.76	7.72
120000	0.2	4.50	5.40	6.29	7.19
130000	0.2	4.21	5.05	5.89	6.73
140000	0.2	3.96	4.75	5.54	6.33
150000	0.2	3.73	4.48	5.22	5.97
160000	0.2	3.53	4.24	4.94	5.65
170000	0.2	3.35	4.02	4.69	5.36
180000	0.2	3.19	3.83	4.46	5.10
190000	0.2	3.04	3.65	4.26	4.87
200000	0.2	2.91	3.49	4.07	4.65

3.3 GENERAL DESIGN CONSIDERATIONS FOR THE USE OF SWELLEX BOLTS

The following is a summary of general design considerations for the use of Swellex bolts which have resulted from the statistical analysis of pull test data.

Pump Pressure

An increase in pump pressure will result in a linear increase in the ultimate load bearing capacity of the bolt. Bolts that were inflated with a pump pressure of less than 27 MPa, performed poorly, as the bolt did not fully inflate. Inflation of the bolt with a pump pressure less than 27 MPa should be done with caution and only in low UCS rocks. In medium to high strength rocks (UCS greater than 50 MPa), at low to normal stresses, pump pressures greater than 30 MPa are desirable, if additional pump capacity is readily available. In highly stressed rock, the additional pump pressure may cause spalling of the rock at the face. In softer rocks (UCS less than 50 MPa), additional pressure may cause excessive plastic deformation of the rock during the inflation process, which will result in a lower ultimate load for the bolt.

Drilled Hole Diameter

The Swellex bolt performs best in the manufacturer's recommended range of 32 mm to 39 mm, with an optimal diameter of 38 mm. Every effort should be made to drill the correct size diameter (38 mm), a difference of even 3 mm has a significant influence on the performance of the bolt.

Elastic Modulus

The elastic modulus of the rock in which the bolt is installed also has a significant effect on the ultimate load bearing capacity of the bolt. The relationship is a negative power function where a lower elastic modulus results in higher ultimate load, as a result, the bolts performed poorly in high elastic modulus rocks. In these rocks a higher pump pressure should be used to achieve an improvement in the ultimate load of the bolt.

Uniaxial Compressive Strength

The UCS of the rock has a significant effect on the performance of the bolt for the lower strength rocks, specifically those rocks, which have a UCS significantly lower than the inflation pressure of the bolt. Inflation pressures higher than the UCS of the rock can cause plastic deformation (as opposed to the elastic deformation that generates the mechanical locking effect of the Swellex bolt), which results in lower slip loads. In lower strength rocks pump pressures higher than the manufacturer's recommended 30 MPa should not be used.

Corrosion and Residence Time

A certain level of corrosion improve the performance of the bolt. However, excessive corrosion and long periods of time (greater than 3 years) cause degradation of the bolt. This results in lower ultimate breaking and slip loads. Swellex should only be used as a means of long term support in low corrosion environments.

Length of Bolt

Longer lengths result in an increased load bearing capacity of the bolt, because of the increase in inflated (anchored) length of bolt. It should be noted that although the ultimate load is the measure of capacity that was used in the statistical analysis, it was used because, for this particular set of data it was considered more reliable than the pullout resistance data (see Section 2.2.3). Ultimate load data was sufficient to assess the relative influence of different parameters. However, Swellex is a frictional bolt and the anchorage is developed over the length of the bolt. The pullout resistance, the load per unit length, is the measure of capacity that should be used for design purposes.

There is a minimum anchoring length required to fully develop the 10 tonnes of capacity for the Swellex bolt. From the data collected for effective length, in which short anchor pull tests were conducted, this minimum development length appears to be approximately 1 metre. However, there is a length beyond which there is no gain in capacity as the steel will break long before this additional capacity is mobilized.

Once the minimum development length has been taken into consideration, the length of the bolt should be designed based on the expected depth of the damage in the rock being supported. There should be a sufficient amount of anchor length both within the damaged zone, and embedded into the rock beyond the damage zone for the bolt to be used effectively. If there is not enough anchored length (< 1m) in the damaged zone, the bolt may break at the faceplate or at the intersection of the damaged zone and the undamaged rock. If there is insufficient anchorage length (< 1m) embedded on the rock beyond the damaged zone, the bolt may be pulled out as this is the effective anchoring length of the bolt. Figure 3-9 is an illustration of this principle.

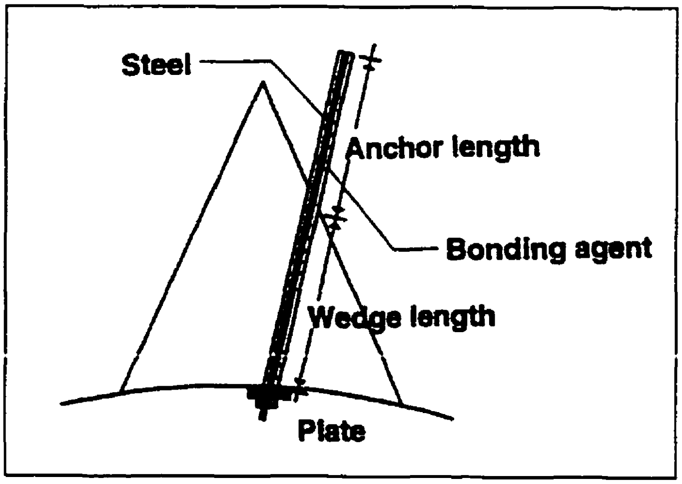

FIGURE 3-9: FULLY BONDED BOLT WITH FACE PLATE SUPPORTING A WEDGE [21]

The anchor capacity is a function of the bond strength, the length of the bolt through the wedge (wedge length) and the length embedded into the rock beyond the wedge (anchor length). The face-plate ensures that there is enough capacity in the wedge part of the system. The capacity is then given by the weakest of the following:

1. Anchor capacity = Anchor Length * τ_b
2. The strongest of:

   Wedge capacity = Wedge Length * τ_b

   Faceplate nut thread assembly
3. Steel capacity[21]

Therefore, the embedded length and the length anchored in the damaged zone should be taken into consideration for the effective use of Swellex bolts.

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[21] Carvalho, J., Hoek, E., and Li, B., Unwedge: Program for Analyzing the Geometry and Stability of Underground Wedges. User's Guide Version 2.3. Rock Engineering Group, University of Toronto, pp 69-70, 1992.

4

STANDARDIZED ROCK BOLT PULL TEST DATASHEET

4.1 CURRENT METHODS OF RECORDING ROCK BOLT PULL TESTING INFORMATION

It became apparent during the course of the research into the performance of Swellex bolts that there is a lack of testing information available and that there was a large degree of variation in the type of information that is recorded when testing is conducted. Swellex testing was conducted sporadically. Basic information (such the results of the test, bolt type and length of bolt), was generally recorded. However, additional information, such as the ground condition parameters (e.g. UCS and RQD) or installation parameters (e.g. pump pressure), which is readily available to the tester, were not recorded.

In other cases (when ground condition information had been supplied), basic information such as the type of the bolt, or even the length of the bolt, was forgotten. Without the bolt length information, even simple data analysis is impossible and the pull test results are rendered meaningless. Obviously, the resistance (which is calculated by dividing the ultimate load by the length of the bolt), cannot be calculated when the length is not recorded. Resistance is one of the primary methods of measuring the performance of most bolts. The other primary method is the ultimate load that the bolt can sustain. Another important result of a pull test is the amount of deformation that the bolt undergoes at each load interval during a pullout test. This information was infrequently recorded. Of the 304 pieces of data that were collected from Swellex pull tests, deformation results were recorded in only 57 cases. Additionally, the units of measure were sometimes omitted. A summary of the pull test information collected in the research into the Swellex bolts is provided in Table 4-1. These numbers reflect the data gathered *after* the mines had been contacted to fill out the information. The numbers were even lower for the data prior to the second data gathering effort. Even basic information such as drill bit diameter and pump pressure was rather sparse.

4.1.1 Lack of Recorded Information

Table 4-1: Breakdown of the Pulltest Information Gathered in the Swellex Study

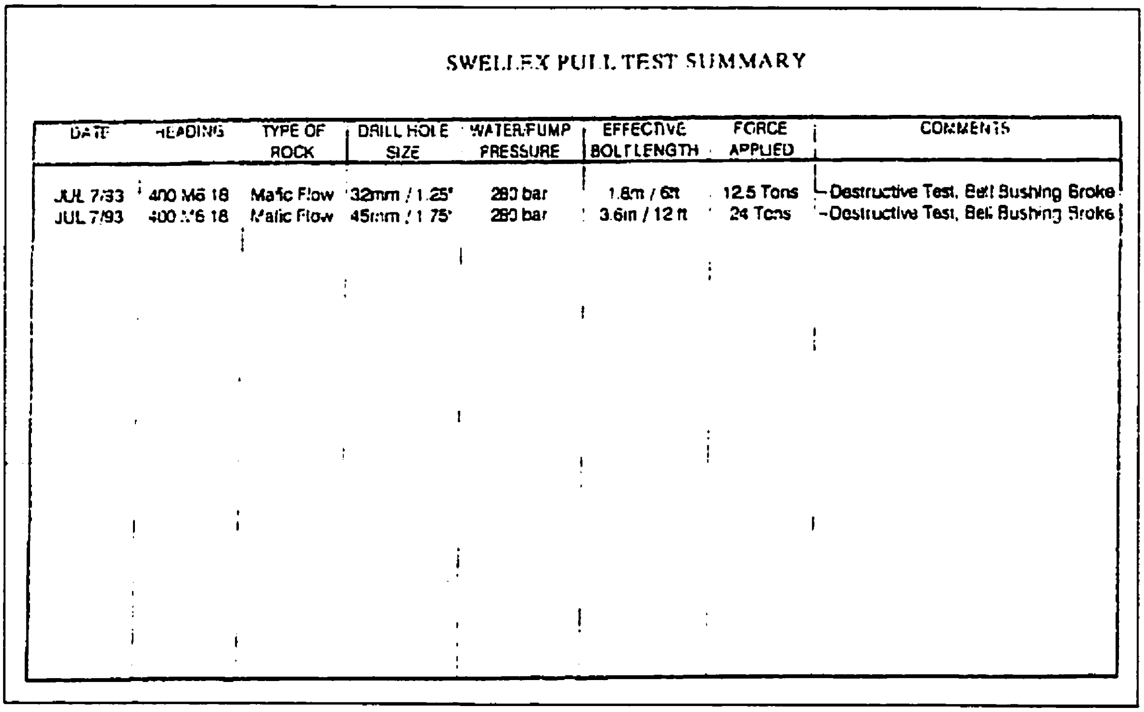
	All Swellex Bolts		**Standard Swellex Bolts**							
	All Tests (304 records)		All Tests (275 records)		Slipped (173 records)		Nondestructive (60 records)		Broken (42 records)	
	No. of Tests	% of All Tests	No. of Tests	% of All Tests	No. of Tests	% of Slipped	No. of Tests	% of Nondest	No. of Tests	% of Broken
Bolt & Installation Parameters										
Type of Bolt	304	**100**	275	**100**	173	100	60	100	42	100
Length of Bolt	276	**91**	248	**90**	148	86	59	98	41	98
Drilled Hole Diameter	183	**60**	183	**67**	129	75	25	42	29	69
Drilled Bit Diameter	51	**17**	51	**19**	23	13	18	30	10	24
Pump Pressure	97	**32**	97	**35**	68	39	6	10	23	55
Inflation Time	4	**1**	0	**0**	0	0	0	0	0	0
Location of Bolt	191	**63**	191	**69**	126	73	45	75	20	48
Pulltest Parameters										
Ultimate Load	304	**100**	275	**100**	173	100	60	100	42	100
Deformation	76	**25**	59	**21**	43	25	12	20	4	10
Corrosion Level	65	**21**	65	**24**	35	20	19	32	11	26
Time Parameters										
Test Date	188	**62**	188	**68**	109	63	58	97	21	50
Installation Date	95	**31**	95	**35**	50	29	30	50	15	36
Residence Time	95	**31**	95	**35**	50	29	30	50	15	36
Ground Conditions										
UCS	99	**33**	69	**25**	34	20	20	33	15	36
Elastic Modulus	26	**9**	26	**9**	11	6	10	17	5	12
RQD	57	**19**	56	**20**	22	13	24	40	10	24
RMR	41	**13**	37	**13**	15	9	16	27	6	14
Q	6	**2**	6	**2**	6	3	0	0	0	0
Lithology	159	**52**	159	**58**	89	51	44	73	26	62
Water Level	64	**21**	64	**23**	33	19	22	37	9	21

From Table 4-1, it is apparent that even the most basic information, which was available at the time of pull testing, was not recorded by some of the respondents. 10% of respondents did not record bolt length information, and in only 97 of 304 tests, pump pressure was recorded (one of the parameters which was found to have a direct influence on the results of a pull test). Inflation time was recorded in only 4 of 304 tests. The ground condition information was another area where information that is generally available to the tester was not recorded. UCS was recorded for about 33% of the tests, and lithology was recorded in 52% of the tests. The other parameters were only recorded in less than 20% of tests, with elastic modulus recorded in only 26 of 304 tests (9% of all tests). Elastic modulus is another one of the factors that was found to have a significant influence on the performance of the Swellex bolt.

4.1.2 Disparity in the Recorded Information

Another difficulty that was encountered was the disparity in the information recorded from mine to mine. Some testing personnel thought it was important to record installation information while others thought that ground conditions information was important. There was also a variation in the manner that the information was recorded. Samples of some representative pull test data sheets are shown in Figure 4-1 to Figure 4-3.

FIGURE 4-1: SAMPLE OF PULL TEST INFORMATION DATASHEET WITH TYPICAL INFORMATION

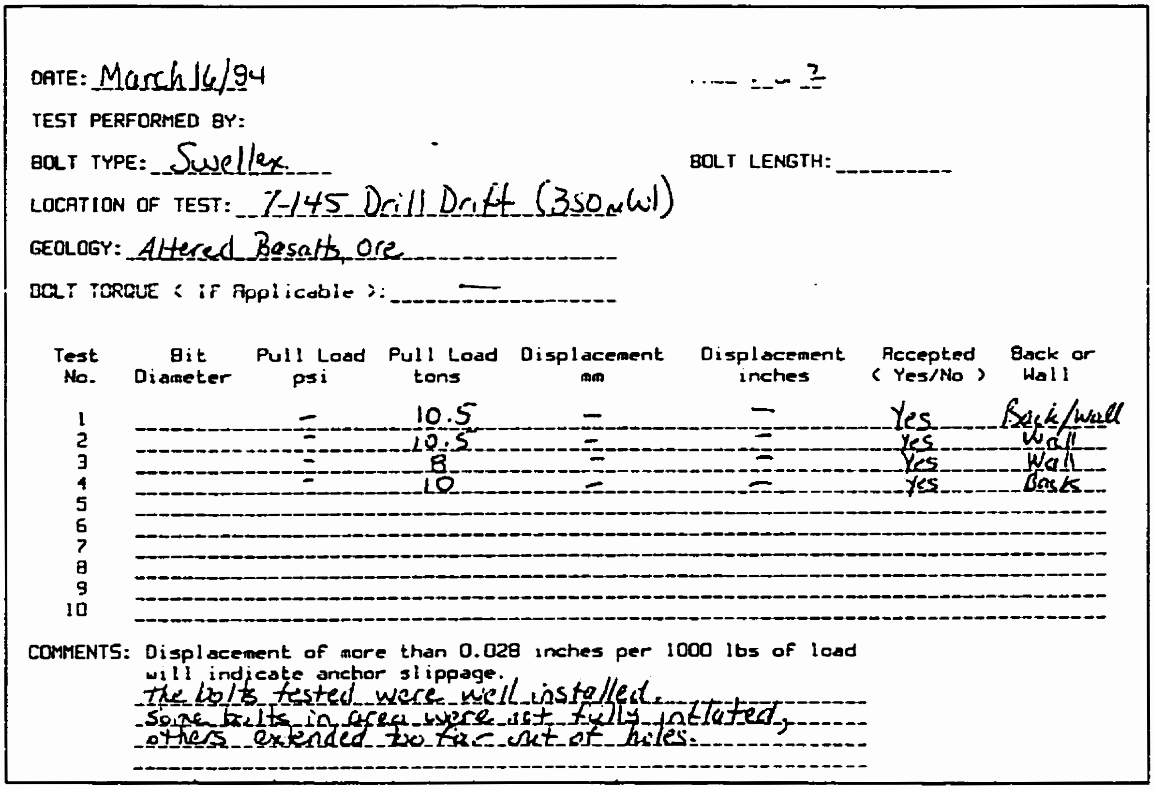


SWELLEX PULL TEST SUMMARY

DATE	HEADING	TYPE OF ROCK	DRILL HOLE SIZE	WATER/PUMP PRESSURE	EFFECTIVE BOLT LENGTH	FORCE APPLIED	COMMENTS
JUL 7/93	400 M6 18	Mafic Flow	32mm / 1.25"	280 bar	1.8m / 6ft	12.5 Tons	-Destructive Test, Bell Bushing Broke
JUL 7/93	400 M6 18	Mafic Flow	45mm / 1.75"	280 bar	3.6m / 12 ft	24 Tons	-Destructive Test, Bell Bushing Broke

The sample pull test record in Figure 4-1 is typical of the amount of information recorded in many of the pull test records. In this pull test record, eight pieces of information were recorded. The length of bolt, the installation pressure, drill bit diameter and test date were recorded. Also, the results and type of test (destructive), as well as the ultimate load at which the bolt broke, was recorded, as was the geology. This example of a pull test record is also typical of the lack of importance that some pull testers place on ground condition information. The format is tabular so that a number of tests can be recorded under each heading.

FIGURE 4-2: SAMPLE OF PULL TEST INFORMATION DATASHEET WITH MORE INFORMATION



DATE: March 16/94

TEST PERFORMED BY:

BOLT TYPE: Swellex

BOLT LENGTH:

LOCATION OF TEST: 7-145 Drill Drift (350mWl)

GEOLOGY: Altered Basalts, Ore

BOLT TORQUE < IF Applicable >: —

Test No.	Bit Diameter	Pull Load psi	Pull Load tons	Displacement mm	Displacement inches	Accepted < Yes/No >	Back or Wall
1		–	10.5	–	–	Yes	Back/wall
2		–	10.5	–	–	Yes	Wall
3		–	8	–	–	Yes	Wall
4		–	10	–	–	Yes	Back
5							
6							
7							
8							
9							
10							

COMMENTS: Displacement of more than 0.028 inches per 1000 lbs of load will indicate anchor slippage.

The bolts tested were well installed.

Some bolts in area were not fully inflated,

others extended too far out of holes.

Figure 4-2 is an example of pull test records in which minimal information was recorded. In this pull test record, bolt type, the test date, geology, location of test, and ultimate load were recorded. Length of the bolt was not recorded here. Also missing, are specific comments regarding the results of the test. From the "Accepted (Yes/No)" column, it was inferred that these were nondestructive tests. These types of inferences regarding the results of the test are typical of the inferences that were made in about 40% of the test records. This format was also used by many of the testers. The background information section is at the top of the page followed by a section which allows for the results of multiple tests to be recorded in table format. A version of this format was used in the Standardized Pull Test Data Sheet created as part of this thesis (Section 4.3).

Figure 4-3 is an example of one of the most complete pull test records gathered in this study. Among the information recorded in this pull test record, is the test date, the age of the bolt, the location of the bolt, geology, UCS, rock structure, length of the bolt, the results of the test and the ultimate load on the bolt. Even with this amount of information, it is not as complete as the ASTM standards recommend.

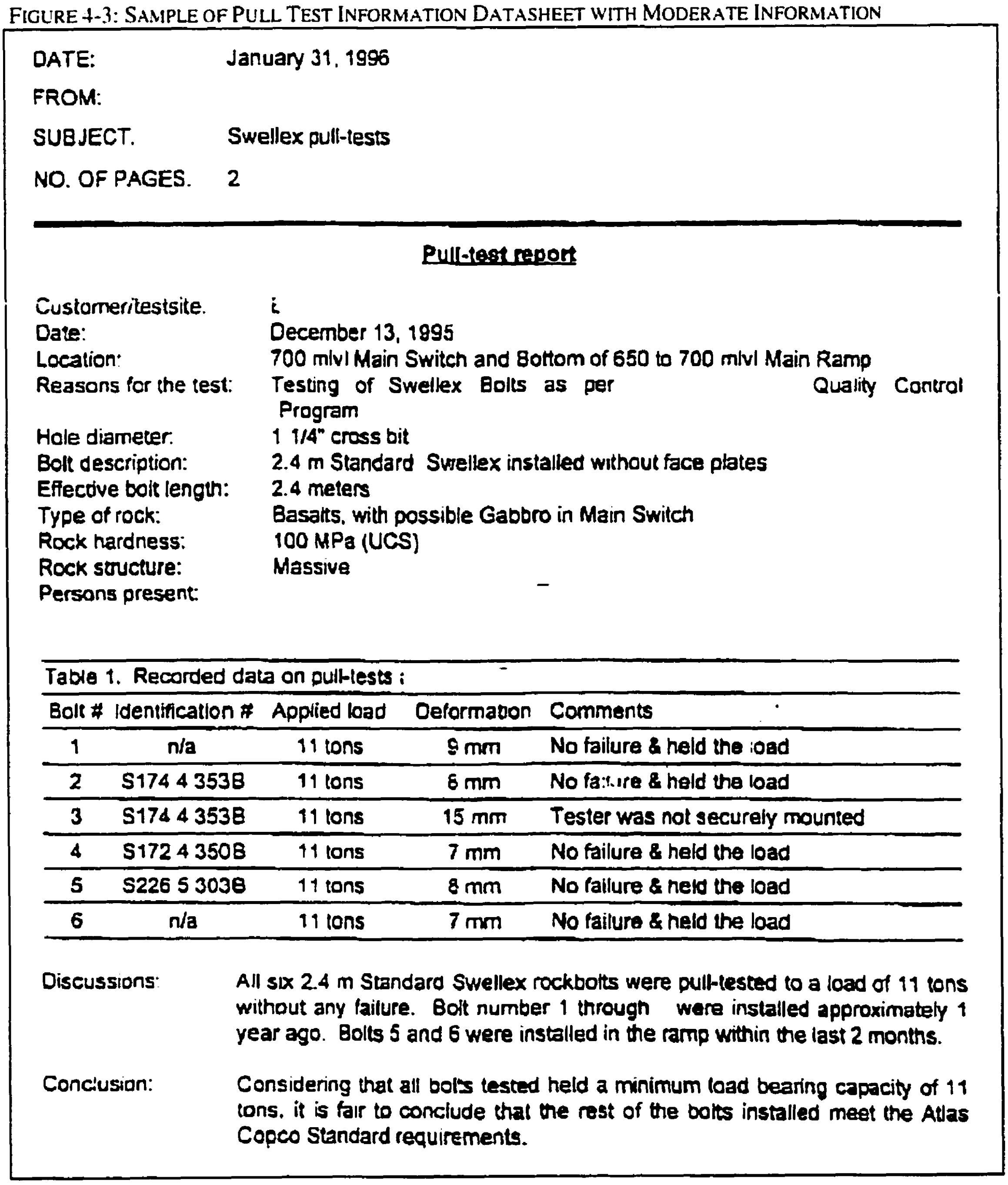


FIGURE 4-3: SAMPLE OF PULL TEST INFORMATION DATASHEET WITH MODERATE INFORMATION

DATE:	January 31, 1996
FROM:	
SUBJECT.	Swellex pull-tests
NO. OF PAGES.	2

Pull-test report

Customer/testsite.	
Date:	December 13, 1995
Location:	700 mlvl Main Switch and Bottom of 650 to 700 mlvl Main Ramp
Reasons for the test:	Testing of Swellex Bolts as per Quality Control Program
Hole diameter:	1 1/4" cross bit
Bolt description:	2.4 m Standard Swellex installed without face plates
Effective bolt length:	2.4 meters
Type of rock:	Basalts, with possible Gabbro in Main Switch
Rock hardness:	100 MPa (UCS)
Rock structure:	Massive
Persons present:	

Table 1. Recorded data on pull-tests :

Bolt #	Identification #	Applied load	Deformation	Comments
1	n/a	11 tons	9 mm	No failure & held the load
2	S174 4 353B	11 tons	6 mm	No failure & held the load
3	S174 4 353B	11 tons	15 mm	Tester was not securely mounted
4	S172 4 350B	11 tons	7 mm	No failure & held the load
5	S226 5 303B	11 tons	8 mm	No failure & held the load
6	n/a	11 tons	7 mm	No failure & held the load

Discussions: All six 2.4 m Standard Swellex rockbolts were pull-tested to a load of 11 tons without any failure. Bolt number 1 through were installed approximately 1 year ago. Bolts 5 and 6 were installed in the ramp within the last 2 months.

Conclusion: Considering that all bolts tested held a minimum load bearing capacity of 11 tons, it is fair to conclude that the rest of the bolts installed meet the Atlas Copco Standard requirements.

4.1.3 Ambiguity in Terminology

Another difficulty that was encountered in the research, a problem which is often encountered in the field of geomechanics, was the ambiguity in the terminology that was used. Terms such as "*very*", "*some*", "*good*", "*bad*" and "*fair*" were used and were very difficult to translate into reliable discrete data. These terms were standardized for data analysis with the understanding that the basis for these terms would vary from individual to individual. Unfortunately, this makes any comparative analysis using these values somewhat unreliable, since one individual's "poor" may be another's "fair"

Additionally, there were problems with the terminology in an even more important area: identifying the results of the test. Midway through the course of the research, after the data had been analysed and was beginning to be processed, a discussion with a Swellex representative provided clarification of the terminology. This resulted in most of the classification of the data being redone. Specifically, when Swellex personnel refer to a test as being '*destructive*' it does not refer to a pullout of the bolt, but rather to the failure of the steel, which generally only affects the first two inches of the bolt. The bolt continues to carry load after a destructive test has been conducted. The destructive test means that the yielding point of steel was attained before the pull out could be attained. A '*slipped*' test was the term that was used by Swellex personnel to refer to a bolt that had slipped out of the hole. Often this result was not recorded, only a load was recorded and the '*slipped*' classification had to be inferred, based on other indications such as comments or from a deformation that far exceeded the normal stretching of steel. Most often, only Swellex personnel would use the term '*slipped*'. Mine personnel who conducted tests would generally not record any kind of classification at all, as shown in Figure 4-2. The classification had to be determined from the ultimate load results, comments and deformation information. Quite a lot of interpretation of the pull test results was required.

Uniformity in the rationale for qualitative information such as corrosion level and water level is required in order to effectively translate the qualitative information into reliable discrete data. The preferred solution would be to develop some quantitative method of describing such data. However, as this method would be time-consuming, it would be unlikely to be used, which would be counterproductive.

4.2 STANDARDS FOR PULL TEST INFORMATION RECORDING RECOMMENDED BY ASTM AND ISRM

The ASTM and the ISRM have developed standards for recording of information during a pull test, in addition to a standard method of conducting a pull test. Not one of the records collected in the research into the performance of Swellex bolts contained as much information as suggested by the ASTM or the ISRM. The standards for both the ASTM and ISRM are summarized below.

The ASTM standard test method for Rock Bolt Anchor Pull Test – D 4435 – 84 (Reapproved 1998) states that,

"8.1 The report should include the following:

8.1.1 Describe the rock material(s) in which the anchors were tested, including the composition, texture and any structural features which could affect anchoring capacity, such as joints, weathering and the like.

8.1.2 Briefly describe the types of anchor tested.

8.1.3 A summary table of the test program including test numbers, anchor type, rock type, orientation and test depth

8.1.4 List the equipment, other than anchors, with the model numbers or dimensions as appropriate. Include the range, accuracy and resolution of the transducers,

8.1.5 Present the equations used to reduce the data including those required to convert transducer output into engineering units.

8.1.6 Prepare summary table of results, including the working and ultimate capacity of each anchor type in each rock type, with anchor type, number of tests, mean working capacity, range and uncertainty of mean,

8.1.7 Include a plot of load versus corrected bolt head displacement of test, and

8.1.8 Append the data sheets for each test."[22]

The International Society for Rock Mechanics (ISRM), suggests that the following information be included in rock bolt pull test record:

Load displacement graph and "...full details of:

(a) rock in which the anchors were tested;

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[22] Standard Test Method for Rock Bolt Anchor Pull Test, Designation: D 4435 – 85 (Reapproved 1998), Annual Book of ASTM Standards 2000, Section Four Construction, Volume 04.08, Soil And Rock, 2000 p.642.

(b) the anchors and associated equipment;

(c) the drillholes, including length, diameter, method of drilled, straightness, cleanness, dryness, orientation;

(d) method and time of installation;

(e) method and time of testing;

(f) the nature of failure and other observations pertinent to the test results"[23]

Most of the pull test records collected into the research into the performance of Swellex bolts did not contain nearly as much information as recommended by ASTM and ISRM. Nor did they contain nearly as much information as would provide a useful pull test record for comparative purposes. In that regard a standardized pull test datasheet has been created (Section 4.3.3) and provided for use.

4.3 STANDARD PULL TEST DATASHEET

A form has been created to promote the recording of data during a pull test, and to standardize the data recorded. The form will be widely available on the internet in order to be downloaded at any time. The form is in Microsoft Excel format. The forms are divided into sections, the most important data to be recorded is listed at the beginning of each section, and the sections appear in the order of importance. Each section contains data which is grouped together by category, such as ground condition information, which is further divided into three subsections: lithology, rock strength parameters and rock mass classification. The information sections integrate the format and information that is currently recorded in practice, with the standards recommended by ASTM and ISRM, the findings of the research into the performance of Swellex bolts, and the previous research into the performance of Split Set bolts.

The purpose of providing the form was threefold. The first is to provide a readily available form that would promote uniformity in the recording of testing information so that the information may be more easily analysed and manipulated. Secondly, the form would promote the recording of more information. Often, not enough information is recorded. Generally, this is because the tester just doesn't think to record the information at the time, not realising the missing information may be useful and in some cases crucial. In some cases the information that is not recorded is obvious to the tester because he or she is the mine engineer is and more than familiar with the information in question such as the ground conditions and the water conditions in the mine. This type of information

(information that is obvious to the tester alone) should be recorded on the form so that the testing information will be more useful within a set of data, when data such as this begins to be shared and analysed. Often the information is readily available, such as ground condition information or estimates of residence time.

Thirdly, the form is entirely compatible with a database that has been created to be a central repository for the rockbolt testing information once it has been recorded. The qualitative information corresponds to the selection options in the database. The form is set up in the same manner as the data entry forms in the database, so that the transfer of information from the paper form to the database is as simple as possible. The database will be described in more detail in the next section of this thesis (Section 5).

A sample of the datasheet is provided at the end of this section. The datasheet is divided into three sheets. The first sheet contains the background information, such as the bolt specifications, ground conditions, drilling and installation information and the resin and grout information. Some of the features of the datasheet are listed below:

The first page is organised with the information that can be filled in electronically in advance and then printed repeatedly. This is so that the mine personnel can enter the general information and the ground condition information once electronically and not have to enter those sections in again unless the testing is conducted in a different set of ground conditions.

Another feature of the information sheet is the '*circle one*' feature in the water conditions and the rock matrix parameters. The choices are qualitative values which are scaled. This removes some of the ambiguity from the terms as the same set of terms is being used by everyone. Additionally, multiple tests of varying types of bolts, drilling and installation can be recorded on one sheet to avoid duplication of data entry.

The second sheet contains the information to be entered obtained from the results of the test: the type of test, the ultimate load, the deformation and the load at which the deformation occurred, the effective length (if it is known), which is the contact/bonded/grouted or inflated length of the bolt. Also the resistance (which is calculated by dividing the ultimate load in tonnes by the length of the

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[23] The ISRM Suggested Methods for Rockbolt Testing, Part 1. Suggested Method for Determining the Strength of a Rock Bolt Anchor Pull Test.

bolt in metres) should also be recorded. The effective resistance can be easily calculated in the same way. The corrosion condition of the bolt is also recorded on the sheet. Again a ranking system from 1 to 5 is used, where 1 is no corrosion, and 5 is very corroded.

The third sheet is used to record specific load deformation values so that a load deformation curve can be recorded as well as information with respect to testing equipment. Again, this sheet can be printed numerous times for each bolt tested.

The use of a datasheet is self explanatory to any person familiar with pull testing. A completed sample sheet will also be provided with the downloadable file along with a cover sheet explaining some of terms used in the sheet. Both the sample sheet and the cover sheet are also included in at the end of this section. A letter which will be sent out by mail and by email to various mine contacts informing them of the availability and purpose of the form and encouraging the use of the form is also included in Appendix A. The email letter will invite the recipient to forward the information to any party they think might be interested in the use of the form and the database. By this means, the mining community will be informed of the form and the database and will hopefully begin to use them, thereby expanding the database and the amount of pull testing data that is available.

4.3.1 Terms and Definitions

Listed below, are some of the terms used on the datasheet that may require clarification:

General Type of Bolt	refers to the general types of rock bolts such as Swellex bolts, Split Set bolts, cable bolts, rebar bolts and mechanically anchored bolts.
Specific Type of Bolt	refers to the classifications such as Standard, Coated, Super or Yielding Swellex, SS33, SS39 or SS46 Split Sets, Birdcaged, or Single Strand Cable bolts.
Drive Time	is the time it takes to insert or inflate the bolt.
Residence Time	is the time from installation of the bolt to the testing date in days.
Test Type	refers to the type of the test or the result or the test. A **slipped** test occurs when the bolt is pulled out of the hole. A **broken** test occurs when some part of the bolt apparatus, including the plates and bushing, breaks. A **nondestructive test** occurs when the load on the bolt is released before the bolt fails or is pulled out.
Ultimate Load	is the load at which the bolt failed – either by being pulled out (**slipped** test), or by breaking (**destructive or broken**), or the highest load that was attained in a **nondestructive test.**
Deformation	is the maximum amount of deformation in mm that the bolt has undergone during the test.
Load at Deformation	is the load in tonnes at which the maximum recorded deformation occurred.
Effective Length	is the inflated, contacting or bonded length of the bolt. The length of the bolt that is actually carrying the load. This parameter is not often known.
Resistance (tonnes/m)	is calculated by dividing the Ultimate load in tonnes by the length of the bolt.
Corrosion	is the condition of the pulled bolt. A ranking system is used where 1 is no corrosion, 2 is surficial corrosion, 3 is little corrosion, 4 is moderate corrosion of the bolt and 5 is a very corroded bolt.

Rock Bolt Pull Testing Datasheet v.1

Contact Name ______________________ Testing Date ______________
Mine/Company ______________________ DD / MM / YYYY

Ground Conditions

Location Name ______________________ General Geology ______________
______________________ Specific Lithology ______________

Rock Strength

UCS (MPa) __________ E (GPa) __________ m-intact __________

Rock Mass Classification

RQD ____ to ____ RMR ____ to ____ Q ____ to ____ GSI ____ to ____

Water Conditions

Dry Dry-Damp Damp Damp-Dripping Dripping Dripping-Wet Wet Wet-flowing Flowing Water

(Circle One)

Bolt Parameters

Test Number(s)	to	to	to
General Type of Bolt			
Specific Type			
Length of Bolt (m)			

Drilling and Installation Information

Drillhole Diameter (mm)			
Drillbit Diameter (mm)			
Pump Pressure (MPa)			
Inflation/Drive Time (m:s)			
Installation Date (DD/MM/YY)			
Residence Time (days)			

Grout/Resin Information

Grout/Resin Type			
Grout/Resin Length (in)			
Grout/Resin Collar Depth (in)			

Additional Comments

Test Number	Test Type	Ultimate Load (tonnes)	Deformation (mm)	Load at Deformation (tonnes)	Effective Length (m)	Resistance (tonnes/m)	Corrosion 1=none 5=very	Comments

Test Type refers to the type of the test or the result or the test, such as a slipped test where the bolts is pulled out of the hole, a broken test, where failure of the bolt involves the breaking of the bolt, or a non-destructive test where the load on the bolt is released before the bolt fails or is pulled out.

Ultimate Load is the load at which the bolt failed – either by being pulled out (slipped test), or by breaking (destructive or broken), or at which the load was released in a non-destructive test.

Deformation is the maximum amount of deformation in mm that the bolt has undergone.

Load at Deformation is the load in tons at which the maximum recorded deformation occurred.

Effective Length is the inflated, contacting or bonded length of the bolt. The length of the bolt that is actually carrying the load. (Not often known.)

Resistance (Tons/m) is calculated by dividing the Ultimate load in Tons by the length of the bolt.

Corrosion is the condition of the pulled bolt. A ranking system is used where 0 is no corrosion, 1 is surficial corrosion, 2 is little corrosion, 3 is some corrosion, 4 is moderate corrosion of the bolts and 5 is a very corroded bolt.

RockBolt Pull Testing Datasheet - Load-Deformation Information v.1

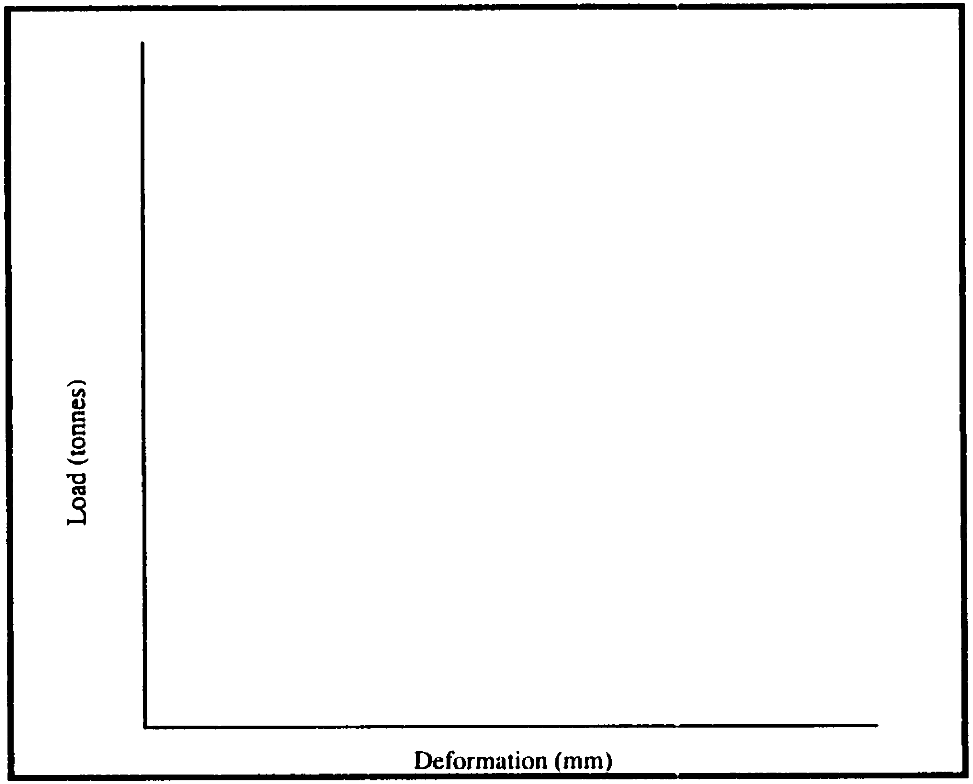
Test Number __________

Bolt Type ____________________

Equipment Description ____________________

Time	Pressure Load Reading	Displacement	Net Displacement

Load-Deformation Curve



Comments

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RockBolt Pull Testing Datasheet v.1

Contact Name John P.Smith

Testing Date 30/09/2000 DD / MM / YYYY

Mine/Company The Gold Mining Company

Ground Conditions

Location Name 400 Level, Hangingwall

The South Mine

General Geology Competent

Specific Lithology Basalt

Rock Strength

UCS (MPa) 200 E (GPa) 150 m-intact ______

Rock Mass Classification

RQD 80 to 90 RMR ___ to ___ Q ___ to ___ GSI 65 to 80

Water Conditions

Dry Dry-Damp [✓ Damp] Damp-Dripping Dripping Dripping-Wet Wet Wet-flowing Flowing Water

(Circle One)

Bolt Parameters

Test Number(s)	1 to 4	5 to 6	7 to 9
General Type of Bolt	Swellex	Swellex	Swellex
Specific Type	Standard	Coated	Standard
Length of Bolt (m)	3.6	2.1	2.5

Drilling and Installation Information

Drillhole Diameter (mm)	38	38	35
Drillbit Diameter (mm)	35	35	32
Pump Pressure (MPa)	29	30	30
Inflation/Drive Time (m:s)	1:30	0:50	1:00
Installation Date (DD/MM/YY)	30/04/1999	30/04/2000	30/05/2000
Residence Time (days)	520	155	125

Grout/Resin Information

Grout/Resin Type	n/a		
Grout/Resin Length (in)	n/a		
Grout/Resin Collar Depth (in)	n/a		

Additional Comments

Test Number	*Test Type*	*Ultimate Load (tonnes)*	*Deformation (mm)*	*Load at Deformation (tonnes)*	*Effective Length (m)*	*Resistance (tonnes/m)*	*Corrosion 1=none 5=very*	*Comments*
1	Destructive	12.0	7			3.33	1	
2	Nondestructive	10.0	7			2.78	1	
3	Slipped	14.1	15	14.1		3.92	2	
4	Slipped	13.2	20	13.0		3.67	1	
5	Slipped	12.8	17	12.8		6.10	1	
6	Slipped	8.0	17	8.0		3.81	1	
7	Slipped	7.8	25	7.8		3.12	1	
8	Broke	8.0	5			3.20	3	Bushing broke.
9	Nondestructive	10.0	7			4.00	2	

Test Type refers to the type of the test or the result or the test, such as a slipped test where the bolts is pulled out of the hole, a broken test, where failure of the bolt involves the breaking of the bolt, or a non-destructive test where the load on the bolt is released before the bolt fails or is pulled out.

Ultimate Load is the load at which the bolt failed – either by being pulled out (slipped test), or by breaking (destructive or broken), or at which the load was released in a non-destructive test.

Deformation is the maximum amount of deformation in mm that the bolt has undergone.

Load at Deformation is the load in tons at which the maximum recorded deformation occurred.

Effective Length is the inflated, contacting or bonded length of the bolt. The length of the bolt that is actually carrying the load. (Not often known.)

Resistance (Tons/m) is calculated by dividing the Ultimate load in Tons by the length of the bolt.

Corrosion is the condition of the pulled bolt. A ranking system is used where 0 is no corrosion, 1 is surficial corrosion, 2 is little corrosion, 3 is some corrosion, 4 is moderate corrosion of the bolts and 5 is a very corroded bolt.

RockBolt Pull Testing Datasheet - Load-Deformation Information v.1

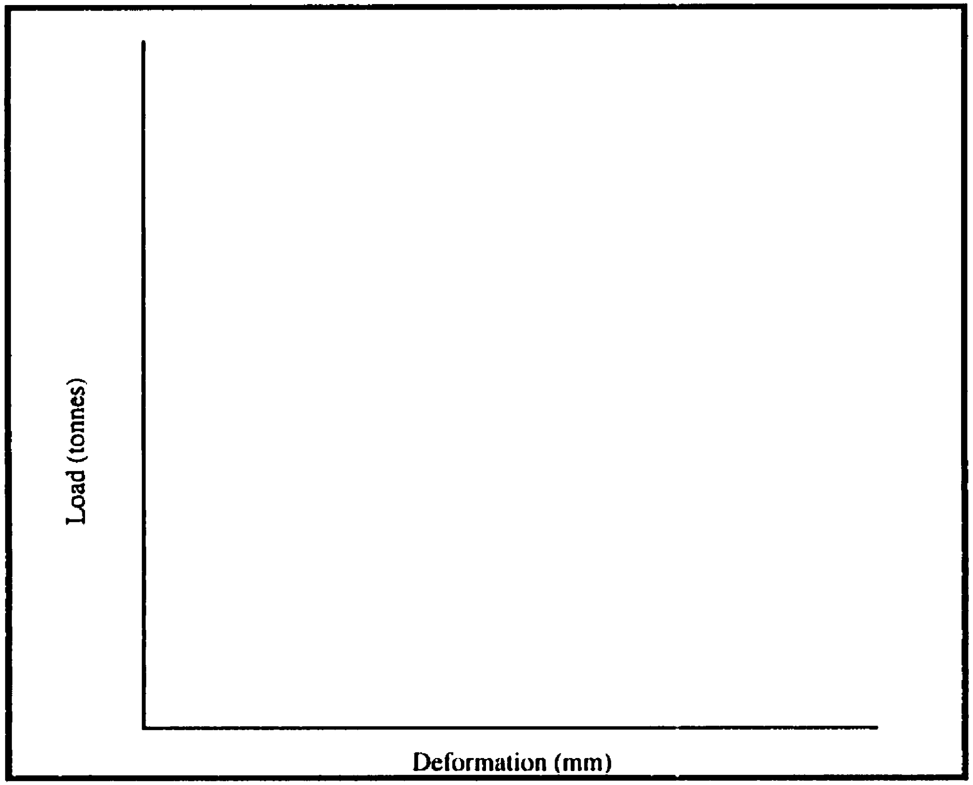
Test Number ____________

Bolt Type ________________________

Equipment Description ________________________

Time	Pressure Load Reading	Displacement	Net Displacement

Load-Deformation Curve



Comments

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5

STANDARDIZED ROCK BOLT PULL TESTING DATABASE

5.0 INTRODUCTION

During the course of the research it became apparent that there was a lack of pull testing information available. This is the result of a lack of pull testing that is being conducted, and also the result of an insufficient amount of information being recorded when a pull test *is* conducted. But it was also due in part to the fact that the existing information is not easily accessible and is often lost with the movement of personnel within the mines. The data collection process was long and arduous and would have been much easier if there was a central repository of information that was easily accessible to those in the mining industry.

More and more, industry is moving towards the use of databases as a dynamic means of storing information that can be easily accessed by large numbers of people. Database data can also be easily manipulated into a useful format. With this in mind, and in consideration of the need for a central location for the pull testing information, a database was created to house the information collected in the research conducted into the performance of Swellex bolts, and in the previous research done at the University of Toronto into the performance of Split Set bolts.[24] Microsoft Access is an industry standard database program which is available to most engineers. For these reasons it is the software with which the Standardized Rockbolt Pull Test Database is constructed and in which it operates. The database is to be freely available and can be obtained by contacting the author, at asoni@golder.com. The database is designed to be used in conjunction with the Standardized Rock Bolt Pull Testing Datasheet described in Section 4, also available through the author at the email address listed above. Both the database and datasheet are also included in the CD provided in this thesis.

5.1 THE NEED FOR A STANDARDIZED PULL TEST DATABASE

When deciding on a method of rock support and evaluating the rock support under consideration or currently in use, mining engineers generally have two sources of pull test information available to them. The first is through their own pull testing program. This information is limited and it can be expensive and time–consuming to conduct the pull test. This is especially true if the engineer wants to conduct a sufficient amount of pull tests to arrive at a statistically reliable value of the ultimate load or resistance of the bolt. The ASTM recommends that 10 to 12 tests be done for each bolt type for each set of ground conditions.[25] This information is also limited to the types of bolts which are currently installed in the mine. Therefore, bolts which have never been used in the mine can only be evaluated based on the other source of information, the product suppliers.

Product suppliers also collect pull test data. However, this data is generally collected with a view to selling product to the consumer, the mine engineer. So observations that reflect negatively on the product may not be readily available. Additionally, these tests are generally conducted under controlled "laboratory" conditions and don't always take into consideration the error introduced with general use, such as installation by mining personnel and degradation over time. Another consideration, is that the information supplied by the product supplier is not always applicable to the conditions for which the mining engineer is designing. The engineer has only the assurances of the product supplier as to the applicability and the performance of the bolt for the engineer's particular mine conditions.

5.2 THE PURPOSE OF THE PULL TEST DATABASE

The purpose of the rockbolt pull testing database is threefold. The first is to standardize the information that is recorded. To that end the database is to be used in conjunction with the datasheet described in Section 4. The database is set up in a similar manner as the datasheet, so as to make the data transfer from the paper datasheet to the database as easy as possible. The ranking system for water level and corrosion is the same, the same parameters for ground conditions are recorded and the information is formatted in the same manner. As well, the same descriptions for the results of the test are used in the datasheet as in the database.

The second purpose is to create a central location where the information can be housed so that it is easily accessible to all. The idea is that the mining engineer will use the Standardized Pull Test Datasheet to record the information when conducting a pull test. Then he or she will send the information by fax or email, or will enter the data recorded on the datasheet into a centrally administered database.

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[24] Tomory, P., Performance of Split Set Bolts, University of Toronto, 1997.

[25] Annual Book of ASTM Standards 2000, Standard Test Method for Rock Bolt Anchor Pull Testing, Designation: D 4435 – 84 (Reapproved 1998), Volume 04.08, p.639, 2000

The third purpose for the database is as a useful design tool. The database can be searched by specific parameters and will return results for the pull test records which fall within the specified search criteria. For example, an engineer may be considering the use of Swellex bolt in his mine. The engineer can then access the database and search the records by General Bolt Type (e.g. Swellex), and by Specific Bolt Type (e.g. Standard Swellex), and by the Lithology (e.g. Talc) and UCS (e.g. 0 to 30 MPa). The database will print a report with the pull test records for all Standard Swellex bolts installed in Talc with a UCS of less than 30 MPa. The engineer can then use the results to assess how the bolt is performing under those conditions in practice. The engineer can then better judge the applicability of the bolt to the conditions in the mine. This information may even be used as an input parameter in modelling software.

5.3 OVERVIEW OF THE DATABASE

A general overview of the Database is provided in the following section. It is designed to introduce the reader to the database, its features and function. However, it is not a step-by-step guide or a manual. The reader is invited to try the database, it is self-explanatory and if questions arise, a help file has been included to answer any queries as to the workings of the database.

There are three primary divisions of the database, the data entry section, the query section, and the report section. The first screen the user encounters is the Welcome Screen shown in Figure 5-1. The first two buttons lead the user to the main part of the database where records can be entered or viewed or the database can be searched.

5.3.1 View Database or Enter New Data Function

The "View Database or Enter New Data" button allows the user to view the existing records or enter new records into the database. This screen shows the general bolt information. The buttons at the bottom of the screen shown in Figure 5-2, launch the dialogs shown in Figure 5-3 to Figure 5-6 in which data can be viewed or entered.

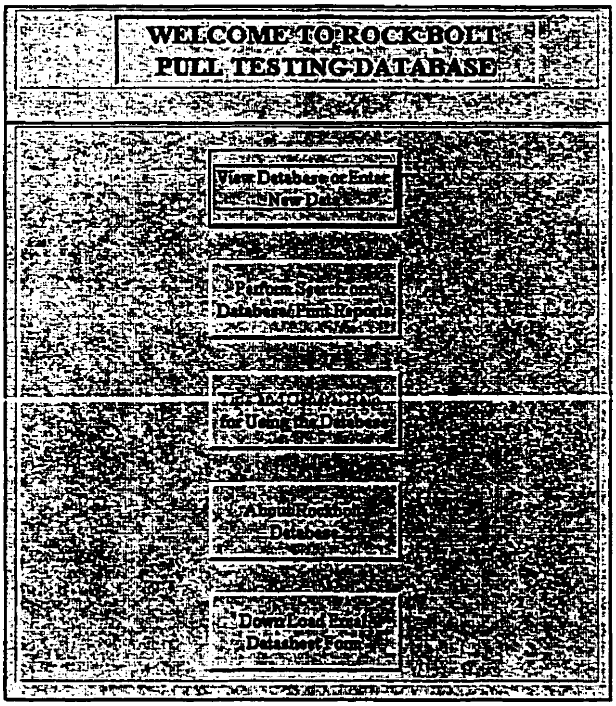
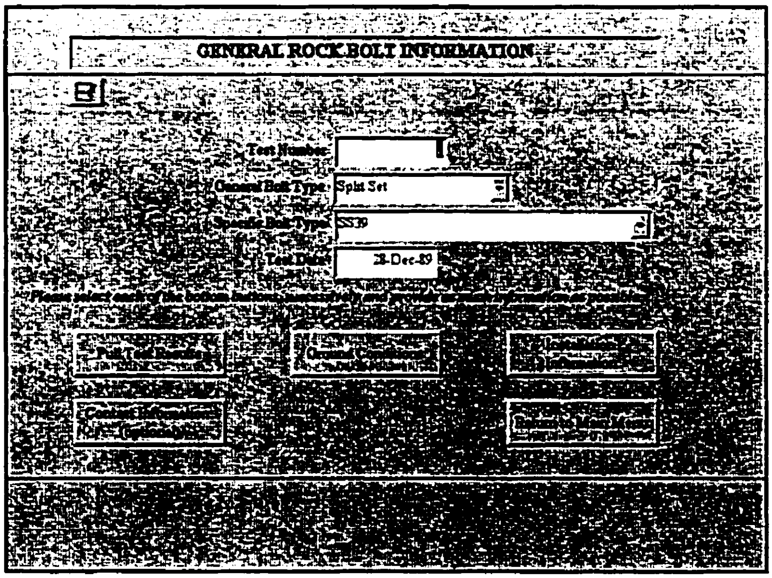
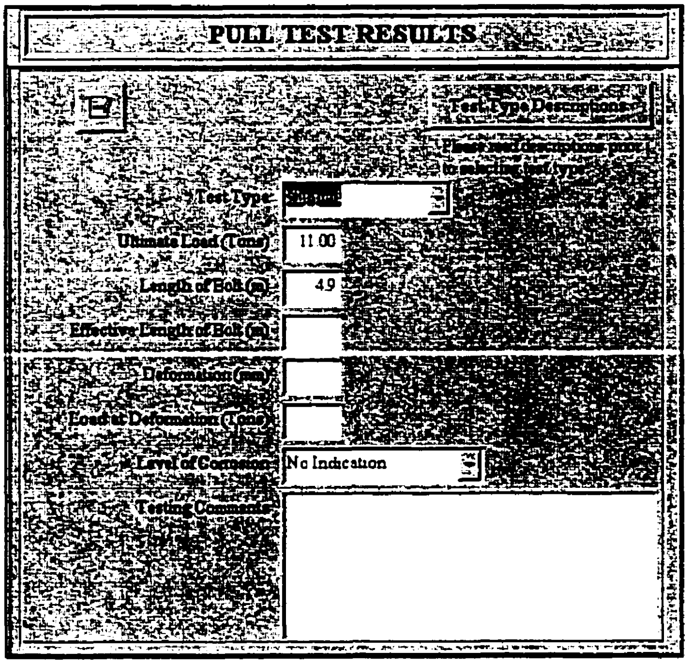


FIGURE 5-1: WELCOME SCREEN FOR THE STANDARDIZED ROCKBOLT PULL TEST DATABASE



Test Number:
General Bolt Type: Split Set
Specific Bolt Type: SS39
Test Date: 28-Dec-89

FIGURE 5-2: GENERAL ROCK BOLT INFORMATION SCREEN



PULL TEST RESULTS

Please read descriptions prior to selecting test type

Test Type:

Ultimate Load (Tons): 11.00

Length of Bolt (m): 4.9

Effective Length of Bolt (m):

Deformation (mm):

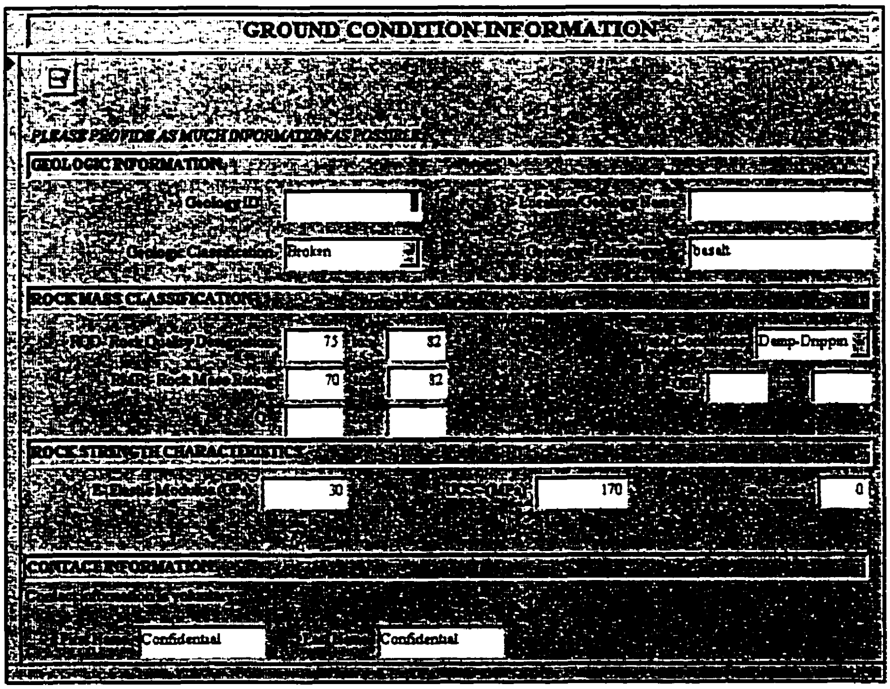
Load at Deformation (Tons):

Level of Corrosion: No Indication

Testing Comments:

FIGURE 5-3: PULL TEST RESULTS SCREEN

The "Test Type Descriptions" button launches a dialog which describes all the test type descriptions: destructive, nondestructive, slipped, and broken tests, so that if the users have any question about the test type descriptions in the pull down menu of the Test Type selection, the descriptions are available.



GROUND CONDITION INFORMATION

PLEASE PROVIDE AS MUCH INFORMATION AS POSSIBLE

GEOLOGIC INFORMATION

Geology ID:

Geologic Classification: Broken

basalt

ROCK MASS CLASSIFICATION

RQD: Rock Quality Designation: 75 82

Damp-Drippin

RMR: Rock Mass Rating: 70 82

ROCK STRENGTH CHARACTERISTICS

E: Elastic Modulus (GPa): 30

170

0

CONTACT INFORMATION

First Name: Confidential

Last Name: Confidential

FIGURE 5-4: GROUND CONDITION INFORMATION SCREEN

The ground condition information can be entered in and viewed from the dialog shown in Figure 5-4. The information about the installation parameters and the grout or resin information can be entered using the dialogs shown in Figure 5-5 and 5-6.

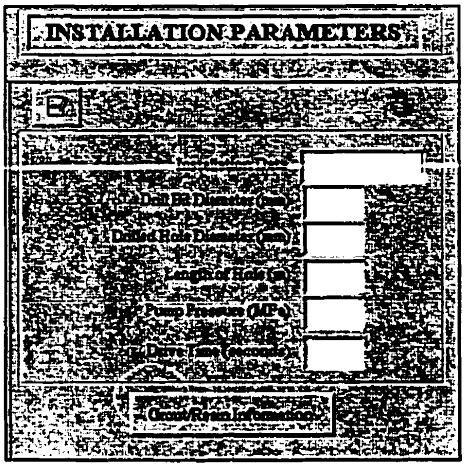


FIGURE 5-5: INSTALLATION INFORMATION SCREEN

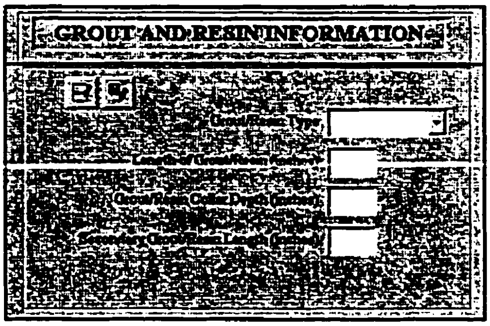
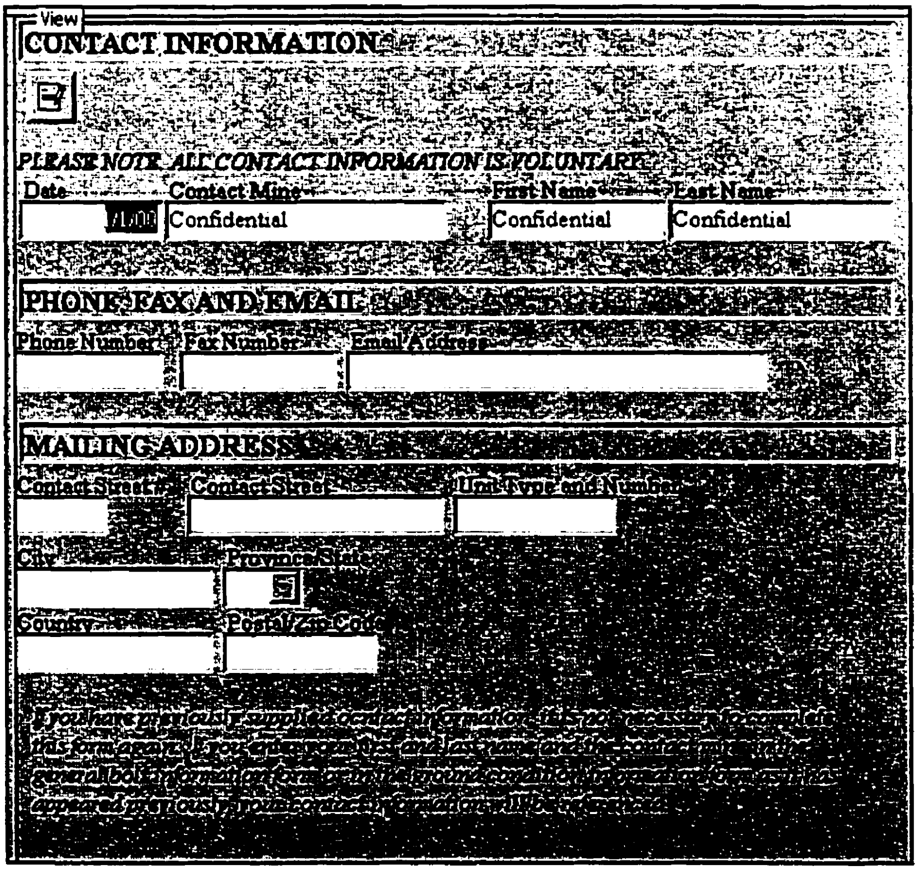


FIGURE 5-6: GROUT/RESIN INFORMATION SCREEN



Contact Mine: Confidential
First Name: Confidential
Last Name: Confidential

FIGURE 5-7: CONTACT INFORMATION SCREEN

Contact information can be viewed or entered in the screen shown in Figure 5-7. Entering the contact information is optional.

Each of the screens shown in Figures 5-2 to 5-7 has a button at the bottom of the screen labelled "DONE" which, when selected, returns the user to the previous screen. Additionally, the down arrow shown in many of the fields in Figure 5-2 to Figure 5-7, when pressed, pulls down a menu with a list of values which can be selected and entered into that field. These pull down menus make the database more efficient to use as it reduces the amount of data entry for the user. It also ensures that nonstandard terminology is not used, and in the case of corrosion level and water level, it ensures that the predetermined ranking system is used. The pull down menus for these fields contain the same values as found in the Standardized Rockbolt Pull Test Datasheet (Section 4).

Another time-saving feature of the data entry portion of the database is that a single contact-information entry may have several different types of ground conditions, which in turn may have several different pull test records associated with each type of ground condition. The data for the contact information and for each of the ground condition entries need only be entered once. This avoids duplication and errors in data entry.

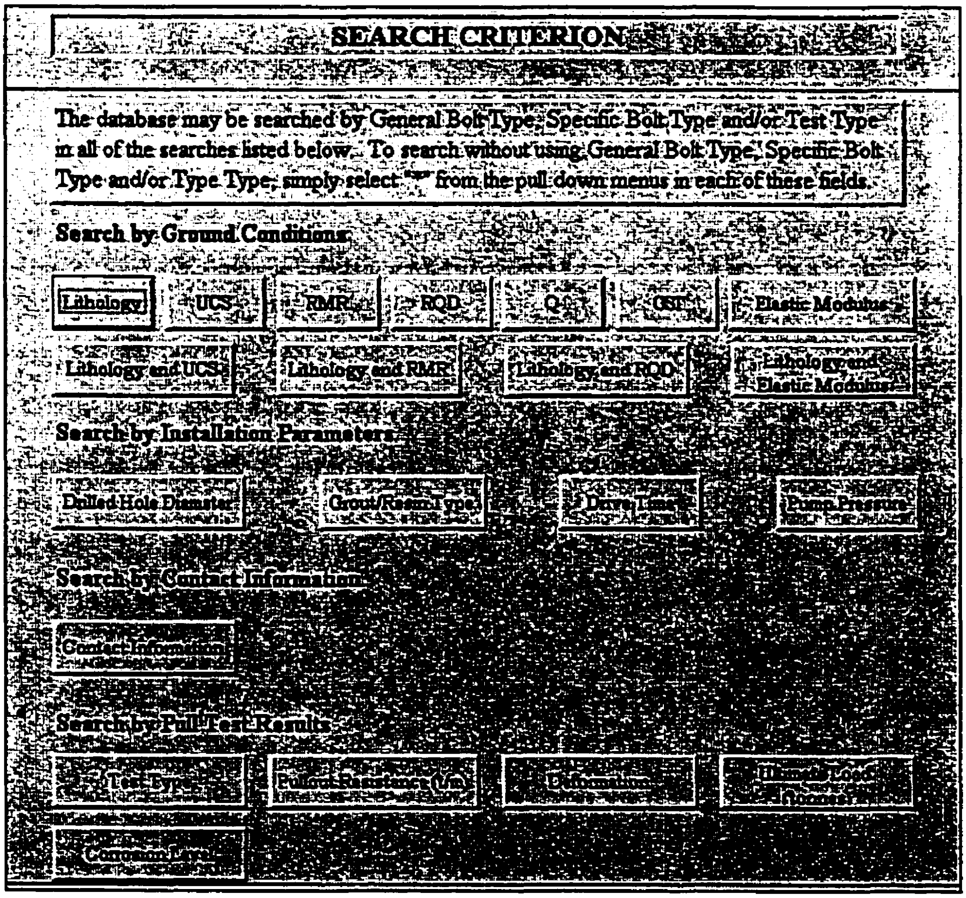
5.3.2 Searching the Database, Queries and Reports

The second button on the Welcome Form, shown in Figure 5-1, launches the search and report generation function. When this button is selected, the Search Criterion dialog shown in Figure 5-8 is launched. When any of the buttons in the Search Criterion dialog, shown Figure 5-8, is selected, it launches a dialog similar to the one shown in Figure 5-9, for Lithology and UCS.

The database can be searched by a number of parameters, up to five, in fact. The selection of General Bolt Type (e.g. Swellex, Split Set, Cable, etc...), Specific Bolt Type (e.g. Standard Swellex, Coated Swellex, SS39 Split Set, Birdcaged Cable Bolt, etc...) and Test Type (e.g. nondestructive, destructive, broken and slipped) is part of every search. Each of these fields require that one value be selected or that the asterisk character, " * ", which represents all values, be selected. When the asterisk symbol (* all values) is selected the search effectively does not filter by that parameter and all values for that parameter are returned. This * (all values) selection is available in all pull down menus in the search criterion screens. Additionally, the database can be searched by one or two more criteria. These additional criteria are shown on the buttons in Figure 5-8. They include, lithology, RMR, RQD, UCS, Elastic Modulus, Q, GSI, drilled hole diameter, pump pressure, grout resin type.

The database can also be searched by contact information, so that an information supplier can view only their own pull test records. Additionally, it can be searched by pull test result information such as test type, pullout resistance, deformation, ultimate load and corrosion level. All parameters with a numeric value allow for searching by a range of values.

When the Run Query button shown in Figure 5-9 is selected, the database will search the records based on the criteria selected in the screen shown in Figure 5-9. A query screen will be generated and the results of the search will be shown in spreadsheet form. The results of this query can then be copied and pasted to a Microsoft Excel spreadsheet where the data can be further manipulated. Statistical analyses can be performed on the ultimate load results, and pullout resistance results, and can be plotted on charts and in histograms. The results of these data analyses can be used in any manner by the ground support engineer for design purposes, or as input into modelling software.



The database may be searched by General Bolt Type, Specific Bolt Type and/or Test Type in all of the searches listed below. To search without using General Bolt Type, Specific Bolt Type and/or Type Type, simply select "*" from the pull down menus in each of these fields.

FIGURE 5-8: SEARCH CRITERION SCREEN

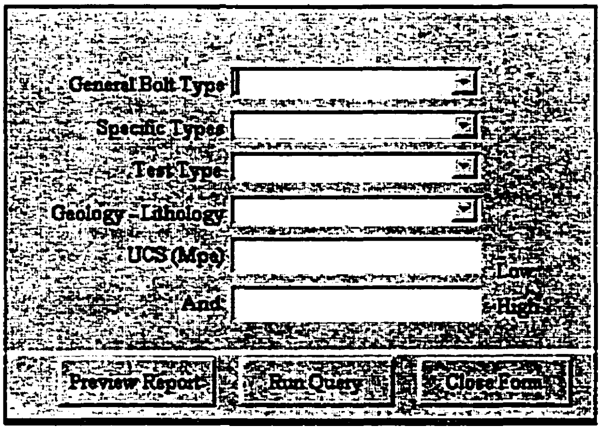
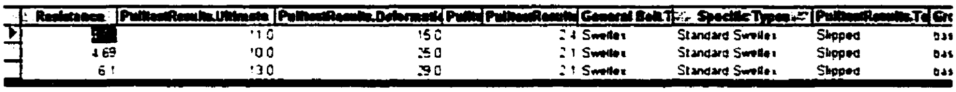


FIGURE 5-9: LITHOLOGY AND UCS SCREEN

An example of the results of a query is shown in Figure 5-10. The filtering criteria for this query are, General Bolt Type = Swellex, Specific Bolt Type = Standard Swellex, Test Type = Slipped Tests, Lithology = Basalt and UCS = 0 to 250 MPa. The results of the query are shown in Figure 5-10.



Resistance	PulltestResults.Ultimate	PulltestResults.Deformatio	Pullte	PulltestResults	General Bolt T	SpecificTypes	PulltestResults.Te	Gr
[illegible]	[illegible]	[illegible]		[illegible]	Swellex	Standard Swellex	Slipped	bas
4.69	[illegible]	[illegible]		[illegible]	Swellex	Standard Swellex	Slipped	bas
[illegible]	[illegible]	[illegible]		[illegible]	Swellex	Standard Swellex	Slipped	bas

FIGURE 5-10: LITHOLOGY AND UCS QUERY SCREEN

Only the first few columns are shown here. However, the results of the query continue to the right, with all the parameters (columns) listed for each record (rows).

When the Preview Report button is pressed, the database performs the same search as shown in Figure 5-10, but in this case a report is generated. A sample report is shown in Figure 5-11 at the end of this section. The report lists all the records which fit the search criteria along with information such as the pullout resistances and ultimate loads for each of the pull tests. Some other parameters for each pull test are also listed, such as corrosion, lithology, and grout or resin type. The search criteria parameters and selection appears in the heading of the report. Additionally, the mean and standard deviation of all of the pullout resistances and ultimate loads are calculated and shown in the report. This is also done for each subset of the data as well. For example, if a search is performed by the following parameters and selections: General Bolt Type = "Swellex", Specific Bolt Type = "Standard Swellex", Test Type = "*" (All Test Types) and ultimate load = 0 to 5 tonnes. A mean and standard deviation are calculated for all of the pull test records returned by that search and also for the subset of pull test records for each Test Type (in each of slipped, broken and nondestructive tests). The results of this particular search are shown in Figure 5-11 at the end of this section.

Pull Test Results: Search by Ultimate Load (tonnes)

Bolt Type: Swellex

Specific Types: Standard Swellex

Test Type: Broken

Resistance (tonnes/m)	Ultimate Load (tonnes)	Deformation (mm)	Length of Bolt (m)	Drilled Hole Diameter (mm)	Grout or Resin Type	UCS (MPa)	Geology - Lithology
1.67	3.5		2.1				

Summary for 'PulltestResults.Test Type' = Broken (1 detail record)

Average	1.67	3.50
Standard Deviation		
Minimum	1.67	3.50
Maximum	1.67	3.50

Test Type: Non-destructive

Resistance (tonnes/m)	Ultimate Load (tonnes)	Deformation (mm)	Length of Bolt (m)	Drilled Hole Diameter (mm)	Grout or Resin Type	UCS (MPa)	Geology - Lithology
1.09	4.0		3.7				mudstone

Summary for 'PulltestResults.Test Type' = Non-destructive (1 detail record)

Average	1.09	4.00
Standard Deviation		
Minimum	1.09	4.00
Maximum	1.09	4.00

Test Type: Slipped

Resistance (tonnes/m)	Ultimate Load (tonnes)	Deformation (mm)	Length of Bolt (m)	Drilled Hole Diameter (mm)	Grout or Resin Type	UCS (MPa)	Geology - Lithology

Test Type: *Slipped*

Resistance (tonnes/m)	*Ultimate Load (tonnes)*	*Deformation (mm)*	*Length of Bolt (m)*	*Drilled Hole Diameter (mm)*	*Grout or Resin Type*	*UCS (MPa)*	*Geology - Lithology*
5.33	1.6		0.3	35			shale
0.67	2.0		3.0	35			
0.91	2.5		2.8	41			sandstone
8.88	2.7		0.3	35			shale
9.95	3.0		0.3	35			shale
5.00	3.0		0.6	32		6	
4.34	3.3		0.8	35		7	
3.75	4.0		1.1	41		34	sandstone
4.73	4.3		0.9	32		6	
4.12	4.4		1.1	41		34	sandstone
4.41	4.7		1.1	41		34	sandstone
2.08	5.0		2.4	33			fish scale
2.08	5.0	127.0	2.4	33			fish scale
2.38	5.0		2.1	32		196	granite
8.33	5.0		0.6	41			diorite porphyre

Summary for 'PulltestResults.Test Type' = Slipped (15 detail records)

Average	4.46	3.70
Standard Deviation	2.79	1.19
Minimum	0.67	1.60
Maximum	9.95	5.00

Summary for 'Bolt List.Specific Types' = Standard Swellex (17 detail records)		
Average	4.10	3.70
Standard Deviation	2.81	1.11
Minimum	0.67	1.60
Maximu	9.95	5.00
Summary for 'Bolt List.Bolt Type' = Swellex (17 detail records)		
Average	4.10	3.70
Standard Deviation	2.81	1.11
Minimum	0.67	1.60
Maximum	9.95	5.00

5.4 CONCLUSION

The results generated in a query can be manipulated in Microsoft Excel or the results of the report can be used as input for modelling software. Additionally, the results can be used to make a comparison of the performance of the bolts in practice to the manufacturer's stated bearing capacity. Inferences about the performance of the bolt under specific ground conditions and installation parameters can be made as well. The results can also be used to assess the applicability of the different bolts for the ground conditions for which the engineer is designing.

Currently, the database houses over 1200 pull test records for Swellex and Split Set bolts which is an excellent starting point. The database will be promoted along with the datasheet, via letters and emails to inform mining personnel of the existence and usefulness of the database. In time, with use and with additional information supplied by the users either electronically or in hardcopy, the database will be expanded to become an invaluable design tool.

REFERENCES

1. Annual Book of ASTM Standards 2000. Standard Test Method for Rock Bolt Anchor Pull Testing. Designation: D 4435 – 84 (Reapproved 1998). Volume 04.08. 2000.

2. Atlas Copco Ltd.. Swellex Product Manual. Swellex – The Engineered Rock Reinforcement System. 1999.

3. Brady. B.H.G. and Brown. E.T.. Rock Mechanics for Underground Mining. Second Edition. 1994.

4. Carvalho. J.. Hoek. E.. and Li. B.. Unwedge: Program for Analyzing the Geometry and Stability of Underground Wedges. User's Guide Version 2.3. Rock Engineering Group. University of Toronto. pp 69-70. 1992.

5. Charette. F. Hadjigeorgiou. J. Guide Pratique du Soutènement Minier. Association Minière du Québec. 1999.

6. Hakansson. U.. and Li. Chunlin. Swellex in Weak and Soft Rock. Proceedings of the International Symposium on Rock Support. Lillehammer. Norway. 1997.

7. The ISRM Suggested Methods for Rockbolt Testing. Part 1. Suggested Method for Determining the Strength of a Rock Bolt Anchor Pull Test. 1974.

8. Kaiser. P.. McCreath. D.. Rock Support in Mining and Underground Construction. Proceedings of the International Symposium on Rock Support. Canada. 1992.

9. Popov. E.P.. Mechanics of Materials. Thin Walled Cylinders. Second Edition. 1978.

10. Stjern. G.. Practical Performance of Rock Bolts. Proceedings of the International Symposium on Rock Support. Lillehammer. Norway. 1997.

11. Stillborg. B.. Rockbolt Loading Across a Tensile Joint. Lulea University of Technology. Sweden.

12. Tomory. P.. Performance of Split Set Bolts. University of Toronto. 1997.

13. Walpole. R. and Myers. R.. Probability and Statistics for Engineers and Scientists. Prentice-Hall. 6th ed.. 1998.

14. Wijk. G.. and Skogberg. B.. The SWELLEX rock bolting system. Rock Breaking and Mechanical Excavation. Canadian Institute of Mining and Metallurgy. CIM Special Vol. 30. pp. 106-110.