Technical Evaluation of Grouted Rock Anchors for Yarder Applications

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Executive Summary

Cable harvesting operations are often conducted in steep terrain which can present many challenges. One of these challenges is the selection of guyline anchoring systems. Due to the shortening of rotation ages, suitable size stumps are difficult to find in the correct position. This, combined with limited room on landings in steep country logging where deadmen or mobile anchors cannot fit, leaves finite options for guyline anchoring systems. This research report evaluates the use of grouted rock anchors as a feasible alternative. Grouted rock anchors are commonly used in the mining and civil infrastructure industries, for example, to stabilise slopes, tie-down transmission towers, or prevent the collapse of mining tunnels. Applying the concepts, failure mechanisms, and installation methods of these anchors, this report investigates whether they are suitable alternatives to the current anchoring systems.

The main goals of this research report are outlined below:

1. Determine if grouted rock anchors are a suitable alternative anchoring system.
2. Provide installation and testing information and methodologies.
3. Provide anchor design information.
4. Investigate other uses of rock anchors in forestry operations.

The first goal was achieved by installing three grouted rock anchors in a steep terrain forest and then testing them. The grouted rock anchors then underwent two tests: an acceptance test, and a performance test. The acceptance test was used to determine if the three anchors were able to hold the combined total design load of 108 tonnes and hence, be compliant with the Approved Code of Practice. The results from the tests showed that all three anchors were each able to successfully hold 36 tonnes without any noticeable failure or structural deformation. However, during the test, it was noticed that standard thimbles are prone to severe deformation which caused a reduction in accuracy of the results Therefore, it was proposed that for future ventures, a solid thimble should be used. The second test, measuring the anchor performance, was conducted to ensure the anchor was safely able to hold the guyline under working conditions. A 100-tonne load cell measured the loads acting on the grouted rock anchor during operations. The results showed that the maximum load acting on the anchor during a four-day testing period was 20.2 tonnes. This meant the grouted rock anchors had a safety factor of ~ 5:1. However, it was observed that the rigging techniques used led to an imbalance in the loading of the three anchors during the test. Therefore, it was suggested that the current rigging should be replaced with a block.

Overall, it was determined after the two tests that grouted rock anchors are a suitable alternative to the commonly used anchoring systems. However, this is only true if the design, installation, and testing are done correctly. This report suggests two scenarios where grouted rock anchors are likely to be used over conventional anchors. Firstly, where there is minimal room on the landing for deadmen or mobile anchors, suitable-sized stumps are also not present. Secondly, where it is environmentally unfriendly or possesses a significant environmental risk to use deadmen or mobile anchors. Again, suitable-sized stumps are not present.

The second goal was completed by reviewing literature and several key grouted rock anchor standards and then establishing installation and testing methodologies. The report summarises a simple process for installing grouted rock anchors, equipment needed, and several installation considerations. These considerations include an assessment of the angle of installation relative to the guyline and the addition of centralizers. The first testing methodology was a sacrificial/investigation test. This test can be used to assess the ground conditions and holding capacities of grouted rock anchors in locations

where previous anchoring has not been conducted or ground conditions are unknown. This test is voluntary but it is recommended to ensure the design of the working anchor is suitable. An acceptance test is then used to confirm that the holding capacity of a grouted rock anchor is equal to or greater than the design load. From the design standards, it is required that all working grouted rock anchors undergo an acceptance test before they are used.

Providing grouted rock anchor design consideration was the third goal of the report. An extensive literature review was undertaken to determine which components of grouted rock anchors can be modified to influence their holding capacity. Five components were found to have a measurable effect on the holding capacity. They were the number of tendons (only applicable to cable bolt and wire rope anchors), the tendon diameter, the embedded length of the anchor, the shape of the tendon, and the grout properties. Some examples of this were adding conical lugs to the tendon increased the holding capacity dramatically as well as increasing the embedded length.

Finally, two other uses for grouted rock anchors were also reported. The first alternative use was a grouted rock anchor supported slash trap. The design was simple with several grouted rock anchors installed onto the stream bank. A large wire rope netting was then attached to the anchors. Comparing this slash trap to other designs, it was found that it not only reduces costs but does not disturb the streambed and also prevents major erosion of the streambanks. However, there were also limitations to this design. The design is unlikely to be suitable for larger catchments that have wider water bodies, and the design cannot be used on streams that do not have steep banks. Due to the larger load that would be acting on the slash trap, that would likely be greater than the design capacity.

The second alternative was the use of grouted rock anchors as tailhold anchors. The mechanisms of a tailhold anchor are like that of a guyline anchor so, the same tiedown anchor theory can be used. The only difference between the two is the size of the loads. Tailhold anchors experience greater loads then the guyline anchors and must therefore be designed to hold larger capacities. The report concludes that with the correct anchor design and installation processes, a safe tailhold anchor could be achieved. However, this relied on whether equipment and/or machines had access to the location. It is also likely that if equipment and/machines can reach the location it would be substantially cheaper and easier to use a mobile tailhold.

Acknowledgements

Firstly, I would like to thank Professor Rien Visser and Lecturer Campbell Harvey for their continued support throughout my project. I would also like to thank Manulife Forest Management NZ (Tokoroa) and Avalon Ltd for giving me this project over my internship and helping me understand the fundamentals of rock anchors. Finally, I would like to acknowledge the constant feedback from the forestry industry that guided my research, especially feedback from James Byron.

Table of Contents

Table of Figures

Table of Tables

1 Introduction

Cable harvesting operations are often conducted in challenging environments. The steep slopes result in minimal room for landings and high landing construction costs. This, coupled with environmental requirements and stewardship, makes it difficult when planning and carrying out cable harvesting operations.

A key element of cable logging planning and operations is the selection of guyline anchoring systems. Anchors are essential in keeping the hauler pole/tower upright under load. New Zealand (NZ) cable harvesting operations commonly use three different anchoring systems: mobile anchors, stump anchors, and earth anchors (deadmen).

However, with the shortening of rotation ages, adequately sized stumps are difficult to find (Copstead & Studier, 1990). This, combined with constraints on landing size and unsuitable soil mass, can leave minimal options for anchor systems.

This research report investigates the use of grouted rock anchors as an alternative anchor system to the three current methods. The report will provide a real-world example of the effectiveness of grouted rock anchors as an alternate anchoring system, an installation and testing methodology, and an overview of designing a grouted rock anchor. The report will also briefly touch on two other applications of grouted rock anchors in forestry operations.

1.1 Premise for research

A forestry management company was overseeing the harvest of an incredibly steep forest in the Central North Island. Due to the topography of the forest, all dirt cleared during construction had to be end-hauled which came at a significant cost. This meant landing size was minimised to keep costs down. However, due to the landing size restriction, one of the crews was unable to get the correct distance between their hauler (Thunderbird TY-90) and the deadmen.

At first thought, the best option was to track down the steep slope and install a deadman there. However, it was later determined that there was a high probability that this newly exposed sediment would make its way into the streams below. Therefore, it was suggested to install grouted rock anchors on the side of the landing instead. This idea was then implemented and showed strong potential as an alternative to other anchors in situations similar.

2 Literature Review

2.1 Overview

Grouted rock anchors are commonly used in mining operations and other civil infrastructure projects including retaining walls, rock slopes, and geotechnical structures (D. Li et al., 2017; Ma et al., 2013). A standard grouted rock anchor consists of four components. The surrounding rock mass, the reinforcement bar, the internal fixture (grout), and the external fixture to the hole (refer to Figure 1) (Bawden et al., 1992; Chen et al., 2015; Chen, Liu, et al., 2021; Ma et al., 2014; Yazici & Kaiser, 1992; X. Li et al., 2017). There are also non-essential components such as centralizers and spacers; these are used to ensure the tendon is in the correct position well in the borehole (Sabatini et al., 1999). There are three main types of rock anchors: rock bolts, cable rock bolts, and wire rope anchors (refer to Figure 2) (Chen, Liu, et al., 2021; Shu et al., 2005). A key advantage of grouted rock anchors according to Jahangir et al, (2021) is that they can hold tensile, shear, compressive, and bending loads. Hence, grouted rock anchors can be used in multiple loading scenarios such as tie-downs, slope and landslide stabilization, and highway retaining walls among others (Sabatini et al., 1999). Tie-down anchors are anchors which are subjected to uplifting forces and are the anchor type that aligns itself the most with the anchors in this report (Sabatini et al., 1999).

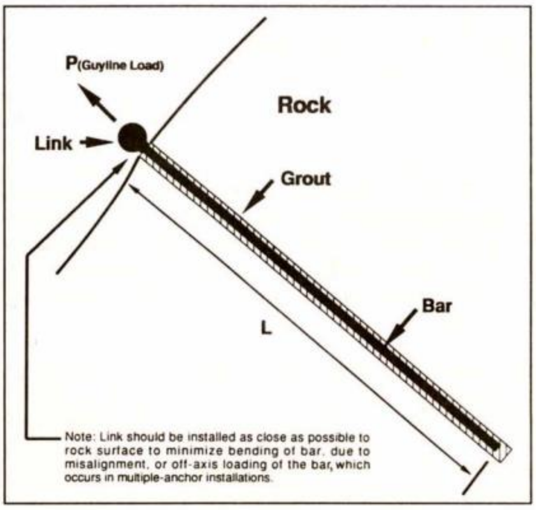

Figure 1 - Main components of a grouted rock anchor

Grouted rock anchors belong to the Continuous Mechanically Coupled (CMC systems). Therefore, the load transfer along the anchor relies on the shear behaviour of the grout (Chen et al., 2015; Hyett et al., 1996). As such, the strength of the three types of grouted rock anchors is mainly frictional, depending on the shear strength at the tendon-grout and grout-rock interface (Kilic et al., 2002). Hence, changes in grout properties and tendon shape influence the holding capacity of the anchor.

Rock bolts are rock anchors using a ribbed reinforced bar as a tendon (Kilic et al., 2002). Whereas wire rope anchors use standard wire rope as the tendon (Shu et al., 2005).

Cable rock bolts are often smaller solid steel rods wrapped around each other (refer to Figure 3}. A key advantage of cable rock bolts is that their mechanical properties allow for greater installation depth compared to standard rock bolts, thus anchoring into deeper and more stable ground/rock mass. However, cable bolts have helically spun wires that, if untreated, are prone to crevice corrosion and are more inclined to stress corrosion cracking (Wu et al., 2018). This is further explored in section 2.5.

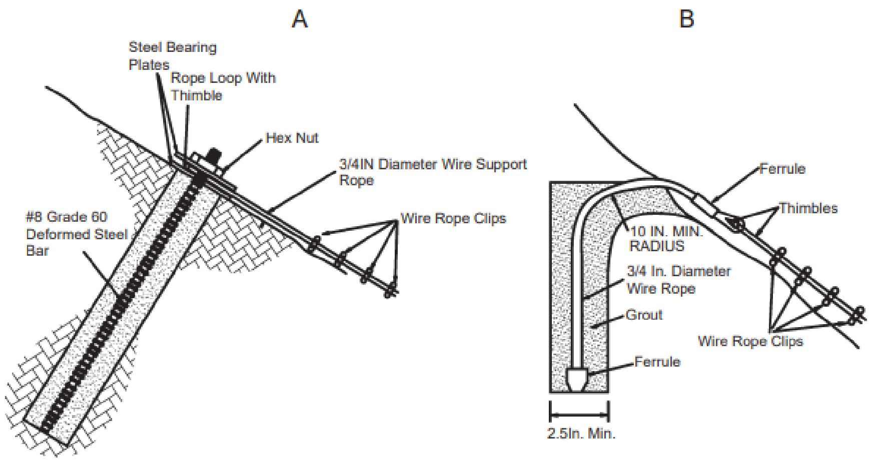

Figure 2 - Comparison of a standard rock bolt and a wire rope grouted rock anchor

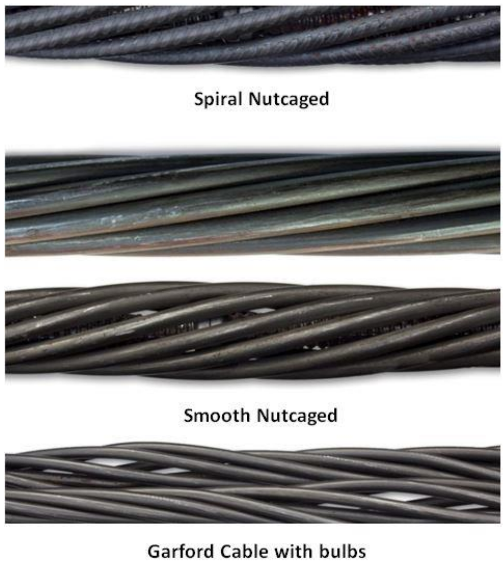

Figure 3 - Example of cable rock bolts

2.2 Approved Code of Practice

The Approved Code of Practice (ACoP) provides rules and preferred actions for guy line anchors in section 14.1. However, these rules are overly simplistic and provide minimal assistance for anchor type or specifications. The main rule/recommendation that applies to this study is 14.1.4.

1. "The configuration used to anchor any operating rope shall be at least equal in strength to the operating rope." (Ministry of Business, Innovation and Employment, 2012).

This recommendation means that an anchor must be equal in strength (holding capacity) to the operating rope, in most cases the skyline. Table 1 below depicts the required holding capacity of a grouted rock anchor based on the diameter of the operating rope used.

Table 1 - ACoP anchor holding capacity requirements based on operating rope diameter (Swaged Logging Rope)

Wire Rope Diameter (inch)	Required anchoring holding capacity (t)
3/4	31.31
7/8	42.62
1	55.78
1 1/8	63.94
1 1/4	78.93

2.3 Best Practice Guidelines

Apart from the Approved Code of Practice, the forestry industry in New Zealand also has access to best practice guidelines to assist with operations. Unlike the AcoP, the Cable logging Best Practice Guidelines (BPGs) provide more detail on what should be taken into consideration when choosing an anchoring system. These are, the number of drags, hauler type, rigging configuration, payload weight and deflection (FITEC, 2005). It also provides details on each of the four anchors (mobile, stumps, earth, and rock anchors) including installation techniques, holding capacity determinants, advantages, and disadvantages.

The rock anchor section explains that grouted rock anchors are commonly used where the soil is shallow and overlies rotten rock and where adequately sized stumps are not present (FITEC, 2005). FITEC (2005) also goes on to suggest that they can be used as anchors for both hauler and tailspar guylines. FITEC (2005) also provides a table of Pro's and Con's which is seen below in Table 2.

Table 2 - Advantages and disadvantages of grouted anchors according to the Bes Practice Guidelines (FITEC, 2005)

Advantages	**Disadvantages**
Can be used in areas with: • Unsuitable stumps • High water tables • Weak, shallow soils over hard bedrock	• Access for installation equipment may not be possible • The best rock may not be in the right place • Costly to set up in time • Cannot be recovered • Must be installed by experienced workers.

Overall, the Cable Harvesting Best Practice Guidelines provide a solid overview of the concept of grouted rock anchors and their potential use in forestry operations. However, the section is lacking in any technical information regarding anchor design, installation, and required testing. Therefore, as of present, it may be exceedingly difficult for forest managers and contractors to grasp the potential positives and negatives of rock anchors. This makes it difficult for grouted rock anchors to be implemented into New Zealand's forestry industry.

2.4 Earth, Stump and Mobile Anchors

As previously mentioned, earth (deadmen), stumps and mobile anchors are the most used anchors in New Zealand. Hence, there is a significant amount of solid literature on their failure modes and holding capacity.

Smith and McMahon (1995) tested several dozen *Pinus radiata* stumps to determine the failure modes and important relationships of stump holding capacity. The results showed that 87% of stumps failed by uprooting and 13% failed by slabbing and shearing. Smith and McMahon (1995) also showed that holding capacities can range significantly between stumps ranging from ~37 to ~110 tonnes.

However, most of the stumps failed between 60 and 80 tonnes. Smith and McMahon (1995) graphed the relationship between holding capacity and stump diameter, showing the two had a strong relationship. Stoupa (1984) came to similar conclusions when conducting similar tests, finding that the relationship between DBH and the holding capacity of stumps had an r^2 of 0.87 indicating a strong relationship.

Fraser and Robison (1998) explored the holding capacity of excavators used as guyline anchors. They found that holding capacity can vary significantly from 25 to 146 tonnes, depending on the weight of the machine, the dipper angle, and the attachment height. For bulldozers, this value was significantly smaller. According to research by Leshchinsky and Russell (2016), bulldozers had a holding capacity between 0.23 and 12.5 tonnes. However, this was not until ultimate failure but until movement of the bulldozer occurred. Therefore, the holding capacities may be significantly greater.

Earth anchors or deadmen are the most popular anchors in New Zealand. Bert et al. (2019) evaluated where deadman get their strength from and defined their holding capacity as:

1. The overburden and passive resistance of the adjacent and overlying soil.
2. The log’s shear and bending strength.

Smith and Stalcup (1966) tested the holding capacity of several deadmen in sandy silt soil. The results showed that deadmen at depths of three and six feet had a holding capacity of ~ 177 and 272 tonnes, respectively.

The few papers explored in this section depict that the current anchoring methods in forestry are highly effective and safe when installed and used correctly.

2.5 Rock Anchor Failure Mechanisms

Guyline anchors share the same mechanical principles of tie-down anchors described in research by Sabatini et al. (1999). They further explained that there are three commonly considered failure mechanisms of these anchors: rock mass failure, shear failure along the rock/grout interface, and shear failure along the grout/tendon interface.

Rock/groundmass failure often occurs in shallow installations where the rock mass is pulled out in an inverted cone ~ 45 degrees from the anchor. Cone failure can also occur in fractured or bedded rock; however, the cone size and shape vary depending on the bedding and cleavage planes (Sabatini et al., 1999). This failure mode occurs when the stress in the surrounding rock exceeds the shear strength of the rock mass (Li et al., 2021; Ma et al., 2013; Shu et al., 2005; Li et al., 2013). The BS 8081:2015 standard stipulates a minimum length of three metres to lower the likelihood of cone failure.

The second failure mode is the failure of the grout medium (grout/rock interface) (Li et al., 2021; Ma et al., 2013; Shu et al., 2005). Sabatini et al. (1999) explain that the grout/rock bond is mobilised progressively in uniform rock due to stress transfer along the bonded tendon thus leading to a portion of the bond length closest to the load elongating and transferring the load to the ground. In this part of the bond-length, resistance is mobilised and the stress is transferred further down. When the stress has transferred to the end of the bond length and the ultimate strength of the grout/rock bond is exceeded, failure at the grout/rock interface occurs and the anchor is ripped out of the borehole (Sabatini et al., 1999). For large diameter grouts, grout failure often occurs in the form of a shear cone (Shu et al., 2005). This happens when the loading stress is greater than the grout’s capacity. This failure mode is a rare occurrence for vertically loaded anchors but normal for horizontally loaded anchors. Horizontal loads cause a passive failure and grout cracking, occurring from the top down as the load increases (Shu et al., 2005).

The literature suggests that failure between the tendon/grout interface is the most common failure mechanism for rock anchors (Chen et al., 2015; Hyett et al., 1995; Ma et al., 2013; Shu et al., 2005). Both Hyett et al. (1995) and Sabatini et al. (1999) concluded that the failure mechanism of the tendon/grout bond involves three elements:

1. Adhesion – Physical coalescence of tendon and grout.
2. Friction – Dependant on the roughness of tendon surface, the size of the slip and the normal force.
3. Mechanical interlocking – Grouts shear strength against tendon irregularities (twisting/ unscrewing).

If the tendon has a smooth surface, the tendon/grout bond is mobilised progressively similarly to the grout/rock bond explained previously (Sabatini et al., 1999). The slip at the tendon/grout interface only occurs after the maximum intensity of the tend/grout bond is mobilised over roughly the entire bond length. Wire rope anchors have a unique feature where their diameter shrinks when loaded; this is more pronounced when the rope is new. This may lead to tendon/grout failure before ultimate bond capacity is reached. However, using crimps or birdcaging the bond strength can be increased. It is also noted that the use of birdcaging may lead to voids in the grout (Sabatini et al., 1999).

Hyett et al. (1995) further explored the failure mechanisms by which tendon/grout failure occurs:

1. Dilational slip with radial splitting
2. Unscrewing
3. Shear failure of the cement flutes

Hyett et al. (1995) found that most of the bond failure for cable rock bolts occurred due to unscrewing rather than shear failure of the cement flutes. They further explained that this failure mechanism is different from a solid rock bolt and that this is due to the helical geometry of the outer wires and the tendons' significantly smaller torsional rigidity. Bawden et al. (1992) came to similar conclusions.

For modified cable bolts the main cause of failure between the tendon/grout bond is due to the dilation slip whereas unscrewing and shear failure effects on failure mechanisms are negligible (D. Li et al., 2017).

There are two other failure mechanisms associated with grouted rock anchors, however, they are not as common amongst tie downs.

Grouted rock anchor failure can also occur in the tendon itself. This happens when the tendon is loaded/stressed in tension. When the load/stress exceeds the structural capacity of the tendon, failure occurs (Sabatini et al., 1999). Often this is the result of using a tendon with a subpar ultimate breaking load compared to the required design or expected loads.

The final failure mode cable is stress- corrosion cracking failure (SCC). Wu et al., (2018) explained that SCC is a dangerous failure mode for the mining industry as it leads to a fast, brittle failure of the tendon. SCC failure occurs when the cable bolt is consistently stressed and subjected to a corrosive environment. The concerning features of SCC failure are that it is difficult to notice the build-up to the failure and that once cracking reaches the critical length, failure is sudden. As stated previously, this failure mode affects the cable rock bolts due to helically spun wires being more prone to crevice corrosion (Wu et al., 2018).

Research by Shu et al. (2005) suggest that the type of failure is influenced by the anchor type, installation methods, grout material, and loading conditions. These factors have been explored further in section 2.6 and have been incorporated into the design considerations section of this report.

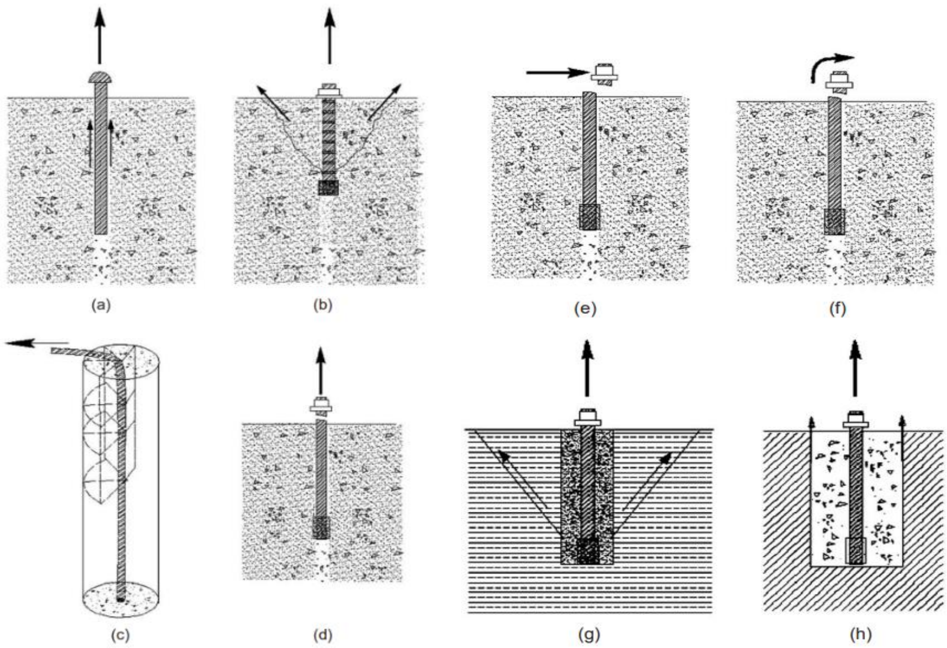

Figure 4 - Common failure modes of grouted rock anchors

2.6 Grouted Rock Anchor Components

2.6.1 Grout Properties

Grout is one of the four key components that make up a grouted rock anchor. Having two-thirds of the failure modes rely on grout performance, the grout or bonding material is incredibly important in the design of the anchor.

There are several grout properties that can be manipulated to change the strength of the grout. Kilic et al. (2002) suggest that too much water can significantly decrease the long term-strength of the anchor. They explained that this was due to the existence of capillary porosities resulting in an unhomogenised internal structure of the grout, causing an irregular stress distribution. Research by Hyett et al. (1995) also found that the bonding strength of a rock anchor is reduced when going beyond a water-cement ratio of 0.4. However, it should be noted that when dealing with low water-cement ratio grouts, the difficulty of installation (pumping of grout) can occur (Kilic et al., 2002). Both Hyett et al. (1995) and Kilic et al. (2002) suggest a water-cement ratio between 0.34 and 0.4 for reliable results. It is also noteworthy that adding sand and fly ash reduces the ultimate compressive strength (refer to Table 2). These additives may also lead to corrosion of the grout if they are not administered in the correct quantities (Kilic et al., 2002). They also concluded their investigation by presenting three options for increasing a rock anchor's bond strength through the manipulation of grout properties (refer to Figure 4):

1. Increasing the shear strength of the grouting material,

Chen et al. (2021) found that increasing the grout's shear strength by one MPa almost doubled the pull-out capacity of the anchor.

2. Increasing the uniaxial compressive strength,
3. Increasing the Young's modulus.

Table 3 - Effects of grout properties on anchor holding capacity

Grout type	UCS_g (MPa)	E_g (GPa)	τ_g (MPa)	P_b (kN)	A_b (cm^2)	τ_b (MPa)	τ_b/τ_g
$w/c = 0.40^a$	5.30	1.15	2.04	16.53	84	1.94	0.95
$w/c = 0.40^b$	12.84	2.74	4.99	43.75	84	5.20	1.04
$w/c = 0.40^c$	17.74	2.96	6.22	55.28	84	6.63	1.07
$w/c = 0.40^d$	20.80	3.39	7.95	57.59	84	6.83	0.86
$w/c = 0.40^e$	22.94	3.79	9.17	59.84	84	7.14	0.78
10% sand[f]	31.60	6.22	6.73	55.45	83	6.73	1.00
10% fly ash[f]	30.58	4.89	7.34	58.15	83	6.32	0.86
5% fly ash[f]	33.33	5.25	8.05	56.01	83	6.73	0.84
White cement[f]	37.72	6.63	8.15	58.15	83	7.03	0.86
$w/c = 0.40^f$	32.01	7.40	10.30	75.26	102	7.34	0.71
$w/c = 0.38^f$	33.33	8.05	10.70	77.39	102	7.54	0.70
$w/c = 0.36^f$	38.94	9.12	11.30	78.99	102	7.75	0.68
$w/c = 0.34^f$	42.00	9.30	11.93	80.87	102	7.95	0.67

Curing time: [a]1 day; [b]3 days; [c]5 days; [d]7 days; [e]14 days; [f]21 days.

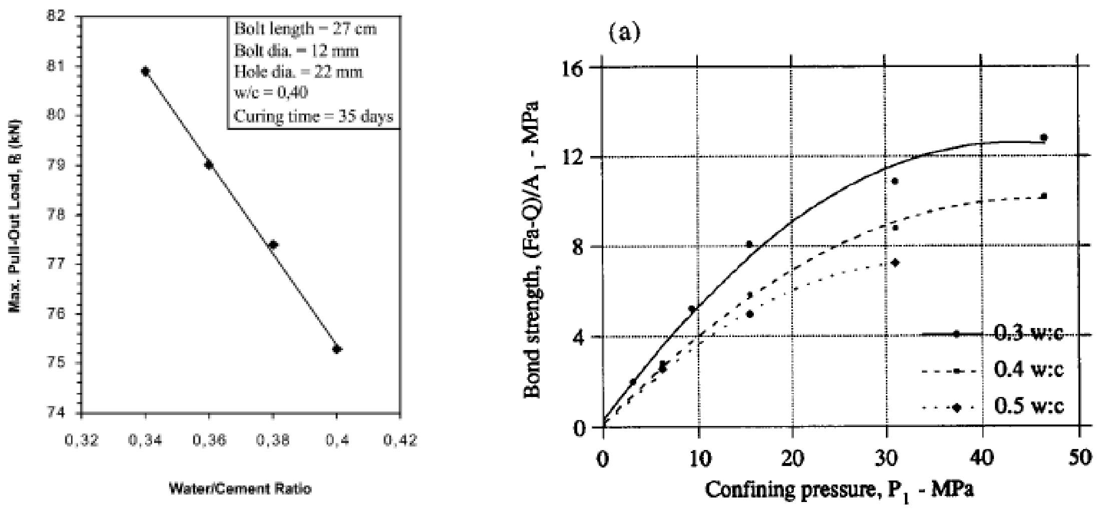

Figure 5 - Effects of grout water:cement ratio on anchor holding capacity

Another property of grout that affects its bond strength is the curing time (Kilic et al., 2002). As depicted in Table 3 above and in Figure 6, increasing the curing time of the grout leads to a substantial increase in the ultimate compressive strength and therefore increases the bond strength of the grouted rock anchor. As expected of concrete after ~7 days majority of the strength has been attained and the curve begins to flatten. It is important when installing grouted rock anchors to allow for an appropriate curing time before they are used or tested.

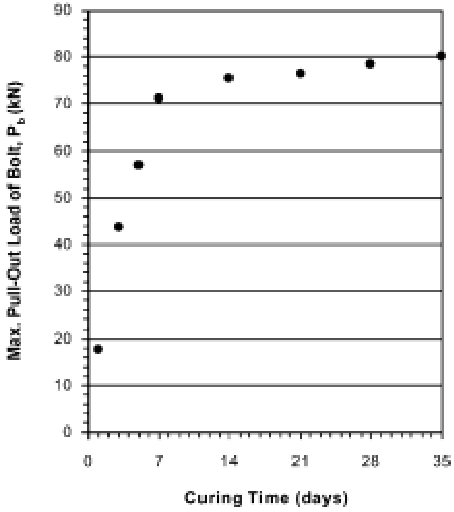

Figure 6 - Relationship between curing time and holding capacity of grouted rock anchors

2.6.2 Tendon Diameter

Research by Kilic et al. (2002), Chen et al. (2021) and Karanam and Dasyapu (2005) showed that an increase in tendon diameter increases the holding capacity of a grouted rock anchor. Further research by X.li et al. (2015a) showed that tendon diameter heavily influences the shear strength of the anchor which led to an increase in holding capacity. Yazici and Kaiser (1992) confirmed this in their study as they found that the bond strength is the "ratio of the pull-out load to the contact area of the bolt". However, Chen et al. (2017) found that once a tendon diameter reached around 300 mm, the holding capacity showed no major increases (refer to Figure 7). Similarly, results were found in research by Rajaie (1990) which showed that bonding capacity became stable at 250 mm diameter.

Chen et al. (2021) found that increasing the bolt diameter increased the holding capacity and reduced the total displacement of the anchor. However, they went on to explain that at large bolt diameters the rock bolt showed brittle behaviour.

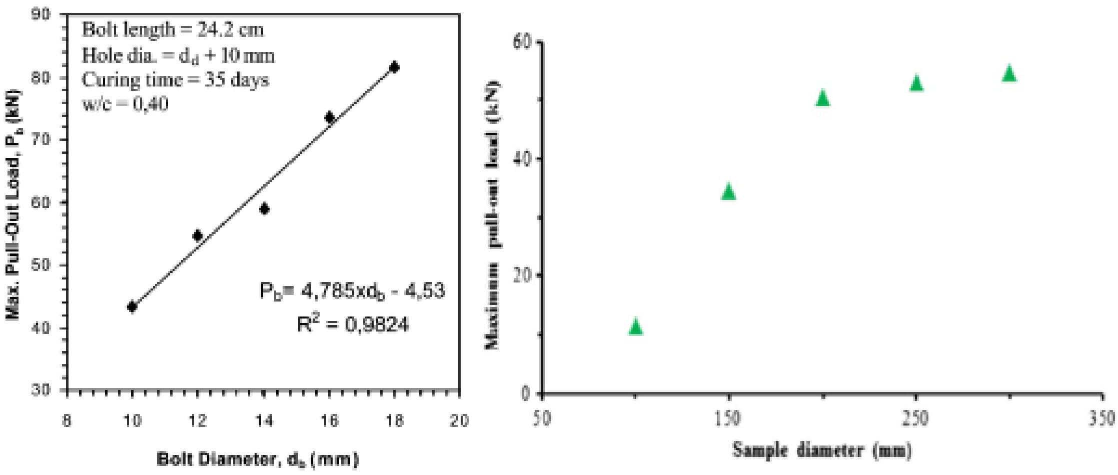

Figure 7 - Effect of bolt diameter on anchor holding capacity

2.6.3 Tendon Length

The holding capacity of a grouted rock anchor increases as the embedded/bonded length of the tendon increases (Benmorrane et al., 1995; Chen et al., 2015; Kilic et al., 2002). Figure 8 shows the results of Kilic et al, (2002) study and as seen the relationship is approximately linear.

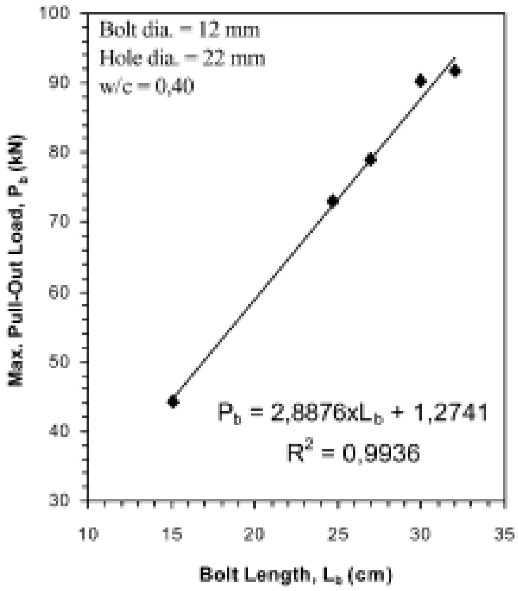

Figure 8 - Effects of bolt length on the holding capacity of grouted rock anchors

2.6.4 Tendon Shape

Kilic et al. (2003) researched the effects the tendon shape had on the pull-out capacity of grouted rock anchors. Five different shapes: single conical, double conical, triple, smooth, and ribbed surfaces were tested at a range of different angles in a pull-out test (refer to Table 9). Their research showed that tendon shape has a noteworthy influence on the loading capacity and failure mode. The most notable was the smooth surface tendon failing at the tendon/grout interface and at a holding capacity four times lower than a ribbed bar. This was due to the smooth tendon having only frictional and adhesion resistance (Kilic et al., 2003). The Triple conical tendons at 15°, 30°, and 45° exhibited tendon failure as the ultimate yield load was 118 kN for the types of tendons used. It is likely that using a tendon with a greater ultimate yield load (strength), the triple conical tendon would have had an increased holding capacity and exhibited a grout-related failure mechanism. The final significant finding in Kilic et al. (2003) research is that the bond strength of cylindrical and ribbed lugged tendons is affected by the shear strength of the grout, and the conical lugged tendons are affected by a combination of the compressive and shear strength of the grouting material. Therefore, as seen in Table 9, the holding capacity of the cylindrical lugged, smooth, and ribbed surface tendons is lower than the angular lugged bolts.

Bolt type	Yield load (kN)	Elastic displacement (mm)	Failure load (kN)	Max. displacement (mm)	Failure type
10° Single conical[a]	56	0.67	67.2	3.62	Grout failure
15° Single conical[a]	56	0.60	65.5	3.75	Grout failure
20° Single conical[a]	48	0.62	62.4	3.70	Grout failure
25° Single conical[a]	48	0.51	61.7	3.60	Grout failure
30° Single conical[a]	48	0.43	60.8	3.50	Grout failure
60° Single conical[a]	48	0.36	59.1	3.41	Grout failure
90° Single conical[a]	48	0.29	57.6	3.25	Grout failure
Smooth surfaces[b]	16	1.10	17.6	1.50	Bolt–grout interface
15° Single conical[b]	64	0.99	68.4	1.78	Grout failure
30° Single conical[b]	64	0.95	65.8	1.40	Grout failure
45° Single conical[b]	56	0.82	63.5	1.30	Grout failure
60° Single conical[b]	56	0.78	60.5	1.26	Grout failure
90° Single conical[b]	56	0.74	59.3	1.18	Grout failure
15° Double conical[b]	88	1.48	92.8	2.60	Grout failure
30° Double conical[b]	88	1.42	89.7	2.71	Grout failure
45° Double conical[b]	80	0.88	87.7	2.35	Grout failure
60° Double conical[b]	80	0.82	86.1	1.87	Grout failure
90° Double conical[b]	80	0.80	84.6	1.69	Grout failure
15° Triple conical[b]	112	0.86	117.5	3.20	Steel failure
30° Triple conical[b]	112	0.91	118.5	3.31	Steel failure
45° Triple conical[b]	112	0.98	118	3.05	Steel failure
60° Triple conical[b]	104	0.96	113	3.60	Grout failure
90° Triple conical[b]	104	1.32	105	2.70	Grout failure
Ribbed surface	88	0.72	92	1.20	Grout failure

[a] Embedment bolt length = 20 cm, Curing time: 7 days.
[b] Embedment bolt length = 30 cm, Curing time: 14 days.

Figure 9 - Effects of grouted rock anchor shape on holding capacity

2.7 Types of Testing

The literature explored in this review has presented several testing types used to quantify the mechanisms of grouted rock anchors. These testing types have been briefly explored below including one of the commonly used industry standards.

Throughout the reviewed literature most of the analyses carried out on grouted rock anchors were in the form of laboratory tests (Benmorrane et al., 1995; Ma et al., 2013; X. Li et al., 2015a; X. Li et al., 2017). These tests are often done to explore the effects change in grouted rock anchor properties have on the holding capacity (Benmorrane et al., 1995; Yazici & Kaiser, 1992), or to build up and develop new models (Chen et al., 2018; Tahmasebinia et al., 2018; X. Li et al., 2019). Two of the most prominent laboratory tests were the pull-out and the shear tests.

For pull-out tests, Kilic et al. (2002) sums up the processes. Several grouted rock anchors are installed into large blocks of rock with a known young's modulus and uniaxial compressive strength. These grouted rock bolts are then axially loaded till failure where the displacement, load, and other observations are recorded. These results are then presented in either tables or graphs and several predetermined equations are also used to calculate parameters such as ultimate bond strength. Pull-out tests can be conducted both in the laboratory or in situ.

Much like a pull-out test, laboratory shear tests are common in the literature. However, there was no research found on in-situ shear testing. Research by Li et al. (2017) detailed several types of shear testing throughout the literature; these are shown in Figure 10 below. As the name suggests the grouted rock anchors are loaded in shear and the results are often compared to the tension capacity to find the effects of shear loading on the holding capacity. Shear tests are not the focus of working grouted rock anchors and are not required to be conducted.

Method	Advantages	Disadvantages
Single shear (Dulacka, 1972)	Different installation angles	Only thin bolts can be tested due to small allowable shear displacement
Single shear (Bjurstrom, 1974; Dight, 1983; Ge and Liu, 1988)	Normal stress can be smoothly adjusted; Different installation angles	Specially designed complex apparatus is required
Single shear (Goris et al., 1996; Spang and Egger, 1990)	Normal force is possible	No bolt pretension; Specially designed apparatus is required
Single shear (Bawden et al., 1994; Hutchinson and Diederichs, 1996)	Different bolt installation angles	The apparatus does not produce the maximum capacity of standard cable bolts in most cases
Symmetric single shear (Grasselli, 2005)	Different bolt installation angles. Symmetric setup intrinsically avoids instability	Only thin bolts can be loaded to failure due to the collapse of concretes; Big Samples
Single shear (British Standard Institution, 2009)	The setup is simple and can be loaded in general compression machines	Small shear force; Steel tube-bolt contact; No bolt pretension; Constant bolt installation angle
Single shear (McKenzie and King, 2015)	No steel tube-bolt contact; No full debonding; Integrated testing system	Big samples; Constant bolt installation angle
Single shear (Srivastava and Singh, 2015)	Adjustable normal force; Large shear box allows a set of blocks assembled together to study a complex situation	No bolt pretension; Specially designed complex apparatus is required
Double shear (Haile et al., 1995; Li et al., 2014)	Bolt pretension can be studied; Tested in a general compression machine	Thick bolts cannot be loaded to failure due to the collapse of concrete. Bolt may not fail at both joints simultaneously
Double shear (Aziz et al., 2003, 2014)	Bolt pretension can be studied; Steel frame avoids the concrete collapse; Tested in general compression machines	Bolt may not fail at both joints simultaneously

Figure 10 - Example of shear tests undertaken throughout the literature (Li et al., 2017)

The other type of testing is numerical simulations. They are often used to investigate the theoretical loading performance of grouted rock anchors. Chen et al. (2021) used the cable structural elements in FLAC3D to model the performance of the tendon/grout interface. Simulation testing is used to predict the behaviour of grouted rock anchors under site conditions without performing laboratory or in-situ testing. This method may be preferred over sacrificial anchor testing due to its minimal costs.

British Standard EN ISO 24477-5 Testing of anchorages is a common standard used for tension load testing grouted rock anchors in in-situ conditions. The standard covers three different testing methodologies: investigation, suitability, and acceptance tests. These tests are used for estimating the holding capacity, checking the suitability of the installation method in in-situ conditions of the site and checking if an anchor will hold the design load respectively. The standard also presents three different methods which the three test types fall under:

- Method 1: The anchor is loaded in incremental cycles and the displacement is measured at the maximum load in each cycle.
- Method 2: The anchor is loaded in incremental cycles and the loss of load over a period is measured (at maximum load after lock off).
- Method 3: The anchor is loaded in steps and displacement is measured over a period at each step.

Apart from testing methodologies, the standard provides details on equipment required and guidance on the presentation of results. The process of determining the pull-out resistance from the results is also given.

2.8 Previous Forestry Applications of Rock Anchors

There was extremely limited published research on the use of grouted rock anchors in forestry operations. However, there is one paper by Schroeder and Swanston (1992) that looked at the use of epoxy-grouted rock anchors. Schroeder and Swanston (1992) suggest that grouted rock anchors can be used when reliable anchor points (deadman and stumps) cannot be used. The approach they used was designing the anchor based on the maximum actual load the guylines experience during operations. Applying a factor of safety, the required holding capacity of the rock anchor was determined. Schroeder and Swanston (1992) have shown that there is potential for rock anchors to be used. However, their design approach is not practical for forestry operations in New Zealand due to the excessive costs involved in their setup.

Research by Hartsough et al. (1992, 1997) investigated the use of tipping plate anchors in rock soils as another potential alternative to standard anchoring systems. However, this is outside the context of this report.

3 Objectives of research

The objective of this research report is to provide forestry contractors and management companies with an alternative anchoring strategy for cable logging operations. To do this the four goals outlined below must be achieved,

1. Determine if grouted rock anchors are a suitable alternative anchoring system.
2. Provide installation and testing information and methodologies.
3. Provide grouted rock anchor design information.
4. Investigate other applications of rock anchors in forestry operations.

4 Methodology

4.1 Determine if grouted rock anchors are a suitable alternative anchoring system

Three wire rope grouted rock anchors were installed on the side of a landing to act as a singular anchor for a cable logging operation in the Central North Island. On inspection, the rock mass on the site was discovered to be papa, a widespread soft, blue-grey mudstone or muddy sandstone. It is classified as a ‘soft rock’ or engineering soil due to it having the physical properties of unconsolidated soil rather than rock. Due to this and the lack of previous anchoring experience in the region, the anchors were over designed to give the forest management and logging contractors more confidence. The design, anchor tendon, and specifications for the anchors can be seen in Figures 11, 12 and Table 4, respectively. The anchors were installed and tested by a professional geotechnical engineering business. The installation and testing methodologies are based on documents provided by them.

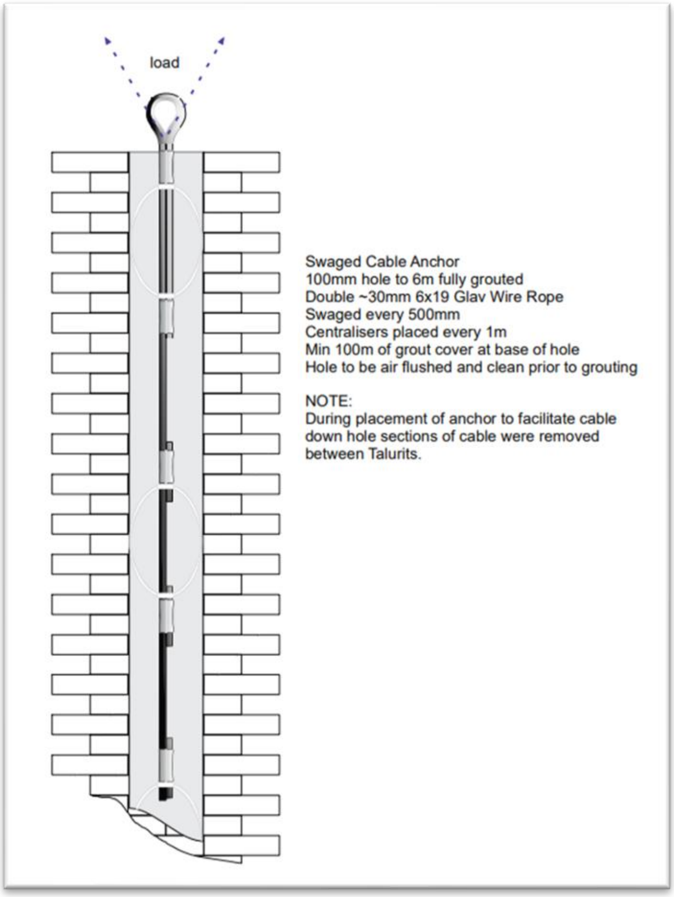

Figure 11 - Wire rope grouted rock anchor design

Figure 12 - Wire rope tendon used in testing

Table 4 - Guyline grouted rock anchor specifications

Anchor Type	Wire rope anchor
Hole Diameter (mm)	100
Wire Diameter (mm)	25.4 or 1 inch
Wire MBL (t)	56.2
Bond Length (m)	6
Unbonded Length (m)	0

4.1.1 Installation Methodology

This section covers the installation methodology used to install the grouted rock anchors. This methodology is not representative of all installations; however, sections can be applied to several scenarios.

1. **Site preparation.**

The first step is to prepare the site for installation. This includes:

- Introducing the installation contractor to the site and proceed with all relevant safety and site preparation paperwork.
- Removing loose rock, overhanging slash, and other obstacles which may impose risk on the safety of those conducting the installation.
- Unload equipment,
  - Pneumatic drilling rig.
  - Temporary access (ASNZSIO 22846-2020).
  - Rope and other abseiling equipment.
  - Anchor tendons.
  - Grout mixing apparatus.
- Mark out the location in which the grouted rock anchor will be installed.

2. **Setup rope and drilling equipment**
   - Setup abseiling equipment for both the pneumatic drill and operators and attach it to the temporary access.
   - Use an excavator to lower the pneumatic drill into position. Ensure that the pneumatic drilling rig is aligned to drill parallel with the guyline as much as possible (refer to Figure 13).

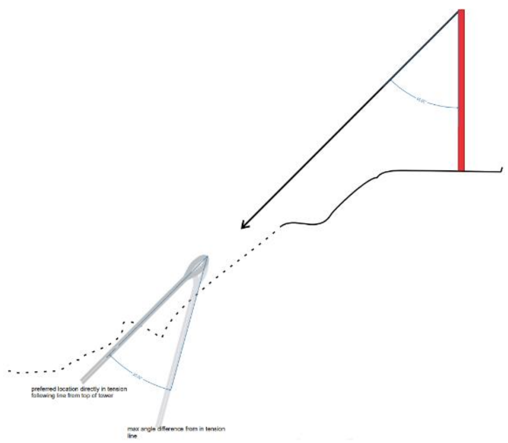

Figure 13 - Grouted rock anchor desired angle of installation

3. **Drilling boreholes**
   - Using the pneumatic drill rig, drill a 100mm diameter hole to a depth of 6000 mm.
   - Air flushing should be used when there are no stability issues found in the rock mass.
   - During the drilling, a drill log is to be filled out noting any changes in rock or soil mass.
   - After drilling the borehole, ensure it is cleaned before proceeding to the next step.
4. **Insert anchor tendon**
   - Using the excavator carefully guide the anchor tendon into the borehole. Ensure the anchor is positioned in the centre.
5. **Grout the Anchor Tendon in Place**
   - Prepare grouting material and mixing apparatus (rotary mixer).
   - Using pneumatic pumps, pump grout into the hole from the bottom up. Ensure there are no air gaps in the grout column.
   - A grouted sample can be taken during this time if required for further testing.
6. **Leave grout to set**
   - As expressed in Table 7 the grout required 7 days for it to reach the appropriate strength. Therefore, it was left for 7 days before any testing occurred.

This process was repeated for all three grouted rock anchors.

4.1.2 Acceptance test methodology

To ensure the strength of the rock anchors are up to the ACoP standard, an acceptance test was conducted on each of the three anchors. This section presents the methodology used to conduct the tests.

1. **Site Preparation**
   - Introduce the testing contractor to the site and proceed with all relevant safety and site preparation paperwork.
   - Removing loose rock, overhanging slash, and other obstacles which may impose risk on the safety of those conducting the installation.
   - Unload equipment,
     - Hydraulic jack and pump.
     - Temporary access (ASNZSIO 22846-2020).
     - Rope and other abseiling equipment.
     - Displacement measuring equipment.
     - Recording equipment.
     - Installation platforms and wedges (reaction system).

2. **Setup Testing Platform**

It is important when conducting grouted rock anchor acceptance tests that the load applied in the test is parallel to the tendon. Due to the sloping of the site and orientation of the anchor a platform for the testing system on the same plane is required.

   - Setup the platform using wooden boxes and wedges.
   - Connect the thimble of the grouted rock anchor to the rebar pole.
   - Place the I-beam on the platform. Ensure the rebar is threaded through the gap.

3. **Setup Testing Equipment**
   - Attach Hydraulic jack and fixing plate to the rebar. Bolt these on tightly.
   - Attach a hydraulic pump to the hydraulic jack and place it in an accessible location.

- Construct another stand-alone platform parallel to the main platform and ensure the platform is fixed and unable to move.
- Attach the base of the displacement device to this newly formed platform with the measuring tool placed on the fixed plate on the main platform.

4. **Conduct Testing**
   - The results recorder will calculate the required PSI for 20, 40, 60, 80, 100 and 120 percent of the required holding capacity. These will be the stages at which the displacement is measured. Displacement should be measured at times 1, 2, 5 minutes for all loads and at times 10, 15 and 20 minutes for 100 and 120 % only.
   - The results recorder is to set up their recording sheet (Table 13) and record results once the test has begun. They will also provide the test conductors with the required loading values in PSI and times at which the displacement will be measured. The recorder will also record any anomalies that occur during the test, usually noted by the test conductors.
   - Before starting the test, the anchor should be loaded to an alignment load, ten kN. Once this was completed the test should begin.
   - One of the two test conductors will use the hydraulic pump to load the grouted rock anchor to each stage while the other will relay the displacement to the recorder on command.
   - Depending on the amount of displacement the displacement gauge may have to be reset. If this happens the recorder must note this and provide the value at which the reset occurs for calibration.
5. **Interpreting Results**
   - Once the test has been completed the results should be uploaded to an excel spreadsheet. There the raw data can be adjusted and corrected for any displacement gauge resets or other gaps in the data.
   - The data should then be displayed in a graph showing the displacement against the applied load.

This testing procedure was repeated for each of the three anchors.

4.1.3 Rigging setup

This section describes the rigging process for the three grouted rock anchors. Each anchor was attached to a 13m x 25 mm wire rope with a thimble on one end. The wire rope was attached using wire rope crimps (tightened to 305Nm), this setup can be seen in Figure 14. The three ropes were then attached together using a Gunnebo Multi Link (SWL of 26T with an RSF of 5:1) which has a breaking load of 130 ton (refer to Figure 15). This was then attached to the guyline.

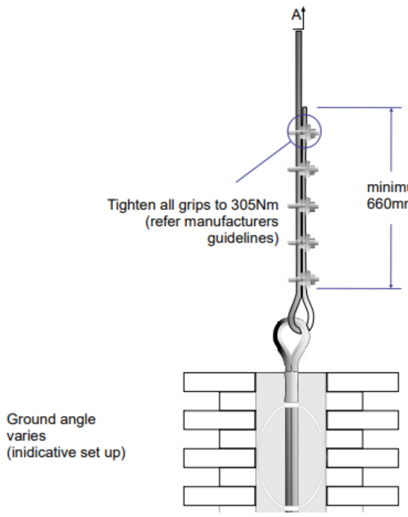

Figure 14 - Grouted rock anchor to wire rope linkage setup

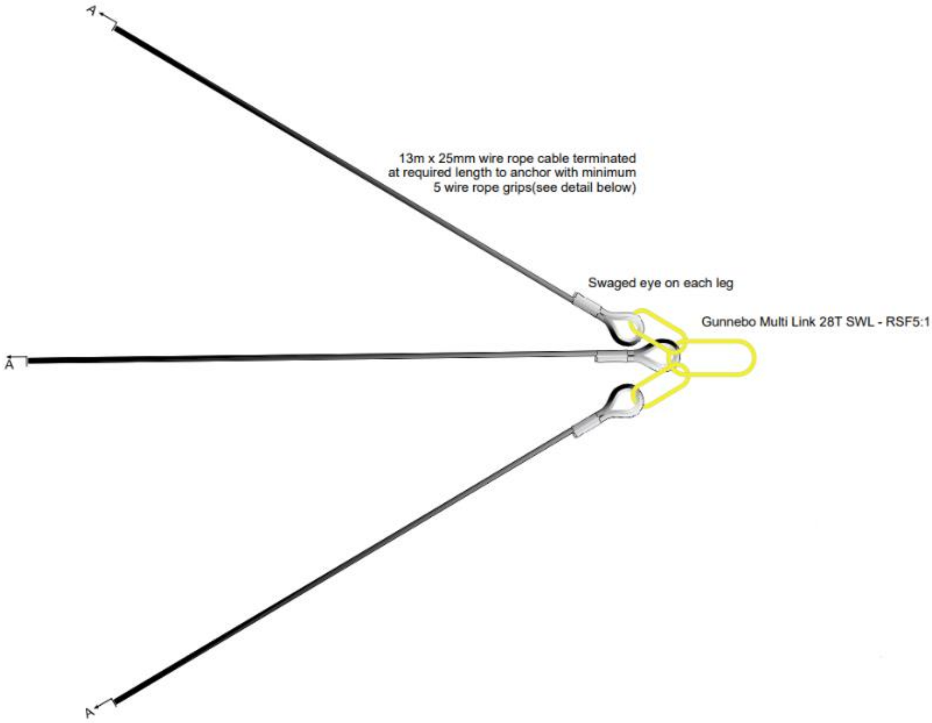

Figure 15 - Final grouted rock anchor rigging setup design

4.1.4 Grouted rock anchor performance test

This section covers the procedure that was used to evaluate the grouted rock anchors performance when under working conditions in a cable logging operation. The anchor performance was tested in two different corridors depicted in Figures 17 and 18. The grouted rock anchors were the main guyline anchor in both corridors. A Thunderbird TY-90 was the hauler used.

1. **Setup load cell**
   - Using an excavator and a lifting strop carry the load cell shackles over to the grouted rock anchors.
   - Let down the closest guyline and remove it from its current anchor.
   - Attach the load cell to the link between the grouted rock anchors and the guyline.
   - Lay the load cell flat, ensure no load is acting on. Then turn it on and zero the load.

- Raise the guyline back to a suitable tension.

2. **Setup measuring apparatus**
   - Find a flat surface no more than 20 m away from the load cell and set up the load displaying device and a recording device (GoPro) to record its display.
   - Ensure the recording device can clearly see the load displaying device.
3. **Starting and finishing the test**
   - Begin the test by allowing the hauler operator to continue working.
   - At each drags end record the number of butts that are brought up.
   - Stop the recording device once the testing has been complete and save it to an appropriate hard drive.
   - Remove, turn off the load cell and store it away correctly.
4. **Sorting data**
   - Using an Excel spreadsheet and the video recording of the loads, input the loads shown on screen.
   - Present the data in an appropriate table or graph.

4.2 Provide installation and testing information and methodologies

As expressed in the literature review section, there is extensive research into grouted rock anchors. A significant amount of this research has been compiled into an FWHA report (Sabatini et al., 1999) and two British standards; BS 8081:2015 and BS EN ISO 22477-5. These three reports will be simplified and condensed to create a simple and concise installation and testing methodology for forestry managers and contractors. Apart from the installation and testing methodologies, this study also covers:

- Installation equipment required.
- A description of the two testing types and guidance on when to use a specific test.
- Provide insights on further reading.

4.3 Provide grouted rock anchor design information

To help contractors and forest managers use rock anchors in their cable logging operations, it is important in this study to include information on rock anchor selection and design considerations. Using literature, geotechnical companies' advice, and lessons learnt from the acceptance and performance test, an in-depth section on grouted rock anchor design considerations was written.

4.4 Investigate other applications of rock anchors in forestry operations

Rock anchors are highly versatile and can be used in many scenarios. This study looks at the potential for grouted rock anchors in other aspects of forestry operations. By researching literature, case studies and advice from geotechnical experts, a case for the use of rock anchors for opportunities listed below was made:

- Slash traps,
- Tailhold anchors

5 Results and Discussion

5.1 Determine if grouted rock anchors are a suitable alternative anchoring system

5.1.1 Test 1: Grouted rock anchor acceptance test

Figure 16 depicts the testing rig used in the three acceptance tests conducted. The test results are presented below in Figure 17 and Table 5. Figure 17 shows that each anchor was safely able to hold a weight of 36 tons with a maximum displacement of ~46 mm. Observations during the test found no noticeable failure of the anchor or the surrounding rock mass. Hence, the total strength of the combined anchor is 108 tons, eighteen tons over the ACoP requirements. Therefore, the anchor is compliant and safe to use.

Figure 16 - Acceptance test setup

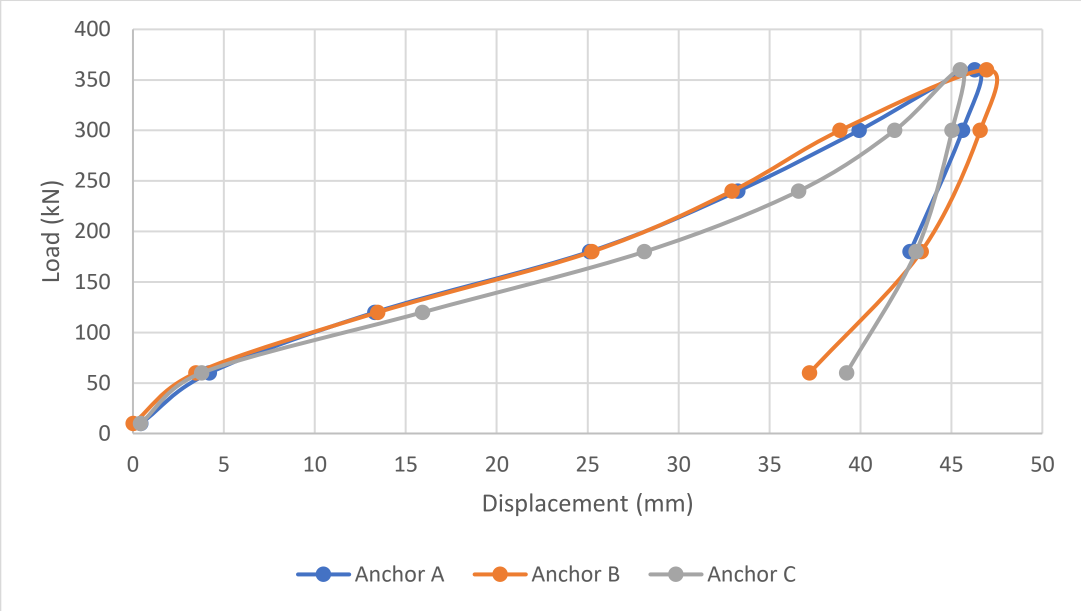

Figure 17 – Load deformation curves for the tested grouted rock anchors

Table 5 - Rock anchor acceptance test results

Load (kN)	Anchor A (mm)	Anchor B (mm)	Anchor C (mm)
10	0.44	0.02	0.42
60	4.21	3.47	3.78
120	13.31	13.47	15.93
180	25.12	25.24	28.13
240	33.26	32.94	36.61
300	39.93	38.88	41.88
360	46.28	46.94	45.5
300	45.61	46.59	45.04
180	42.73	43.34	43.06
60		37.21	39.24

5.1.2 Test 2: Grouted rock anchor performance tests results

5.1.2.1 Corridor one

Corridor one was studied for two days with a total of six hours of data. The corridor's terrain can be seen in Figure 18, noting that the span was ~420 metres and the deflection was relatively good per the crew foreman's assessment. The guyline tested was directly behind the corridor therefore, it was under the most load during operations (main guyline). The crew used a shotgun carriage with three strops attached and the average butts per drag was ~1.5 with shorts not being counted. The results of the test are depicted in Table 6. With a peak load of 20.2 tonnes and an average load of 14 tonnes, the rock anchor has a safety factor of ~ 5:1 for this scenario.

Table 6 - Performance test results for corridor one

	Anchor
Average peak load (tons)	14
Maximum peak load (tonnes)	20.2

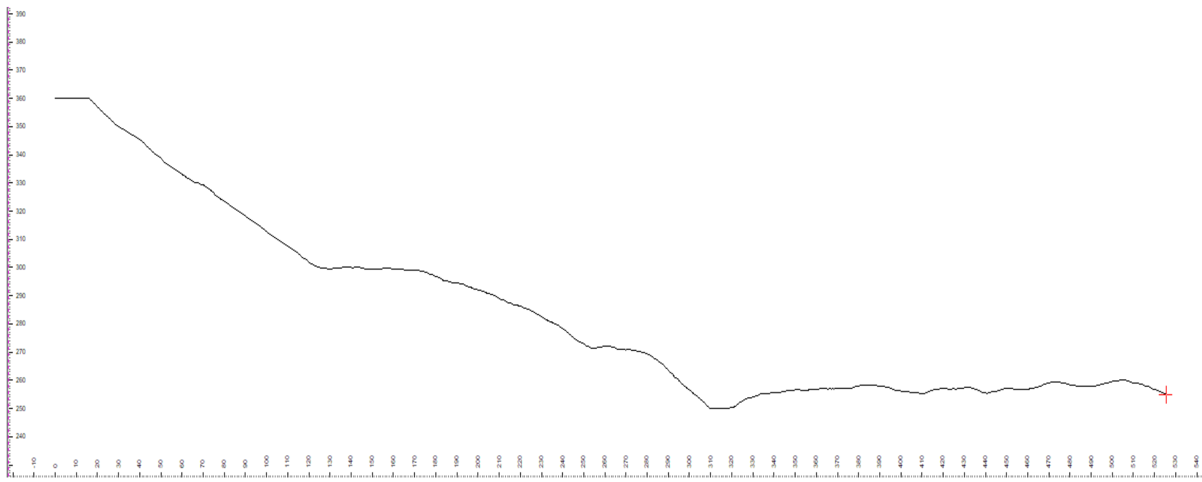

Figure 18 - Terrain profile of corridor one

5.1.2.2 Corridor two

Corridor two was also studied for two days with a total of 4 hours of data collected. Figure 19 depicts the corridor's terrain, the span was ~ 280 metres, and the deflection was excellent. Due to the limited timber and length of the corridor, the skyline was not used. The crew instead used a technique called scabbing. The majority of the logs were butts and hence, the average number of butts per drag was two. The results are depicted in Table 7. Compared to corridor one the loads experienced by the rock anchor are four times less. Therefore, for this scenario, the safety factor was 22:1.

Table 7 - Performance test results for corridor two

	Anchor
Average peak load (tons)	3.5
Maximum peak load (tons)	4.9

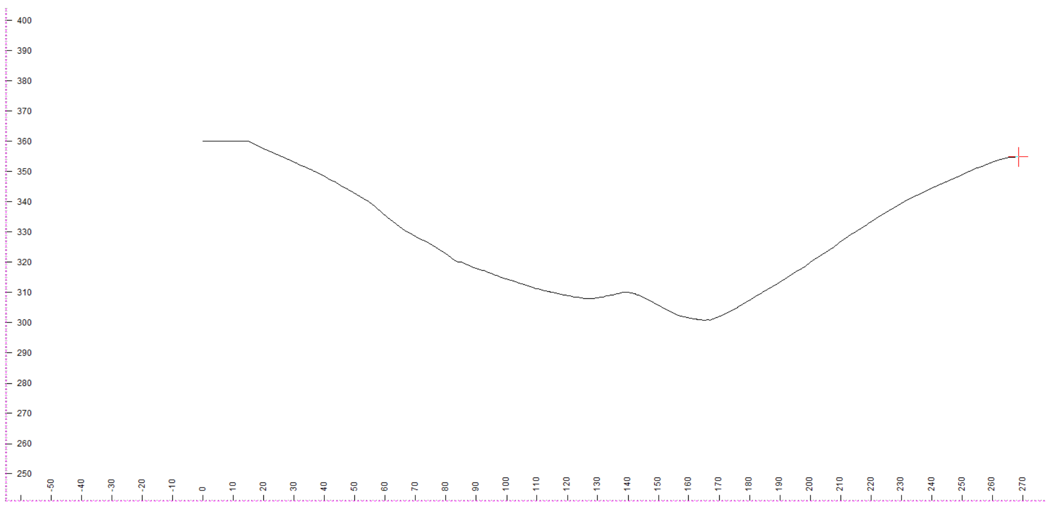

Figure 19 - Terrain profile of corridor two

5.1.3 Rigging of multiple grouted rock anchors

During the rock anchor performance tests, two problems with the rigging of the anchors were noticed.

The first problem was that the rigging was incorrectly installed; this is depicted below in Figure 20. On the right is the correct and proposed design of the rigging, however, on the left is the actual outcome. Based on theoretically ideal angles the loading on the multi-link in the proposed design evenly disturbs the load over the three anchors (33% each) whereas the actual rigging loads the two anchors on the right with 30% of the weight and the anchor on the left with 40%. Therefore, if loads greater than 90 tonnes were exhibited on the anchor it would no longer be compliant with the ACoP. As the load would have exceeded the design/test load.

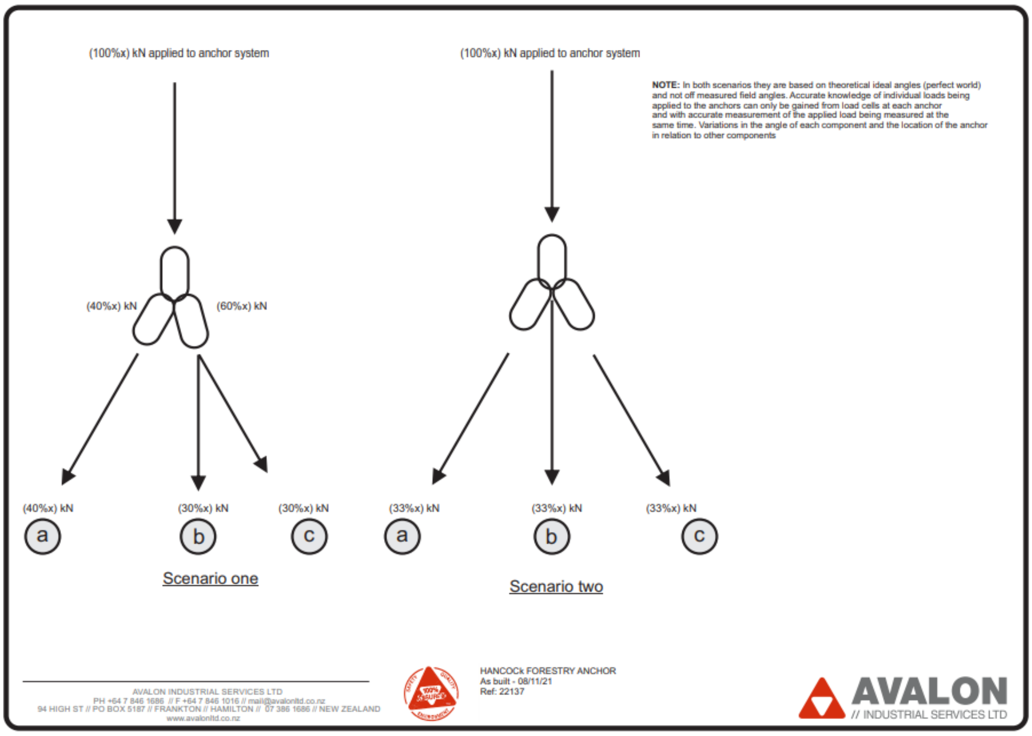

Figure 20 - Rigging design vs what was installed

The second problem was the rigging method itself. It was noted that during the rock anchor performance test that the balancing of the rigging was significantly off. Figure 21 depicts this imbalance, as seen the leftmost and middle anchor are both slack and are not carrying any load. Hence, the anchor on the right is the only grouted rock anchor supporting the guyline. Now based on the results from the rock anchor performance test it is unlikely that a load above 36 tonnes would be placed on the anchor during standard operations. However, this may not be the case if shock loading were to happen or snapping of other loaded guy lines. The main concern is that if an incident involving the rocks anchors was to occur due to the imbalanced rigging the anchor itself is no longer compliant with the ACoP.

There are two possible options to fix this issue. Firstly, whenever the hauler was adjusted, the rigging of rock anchors must also be adjusted. This option is not only extremely time-consuming and labour-intensive but it involves significant guesswork, and it is unlikely that each anchor will be loaded equally. The second option is to remove the multilink and replace it with a self-correcting system i.e., a rigging block. The downside to this solution is the added cost of purchasing the block.

It is recommended to contractors and forest managers to err on the side of caution and use a self-correcting system when rigging multiple anchors together.

Figure 21 - Imbalance in the rigging of the trio of grouted rock anchors

5.1.4 Displacement of anchors

The results from the acceptance test show that there was a significant amount of displacement during the tests, an average of 46.24 mm. After further investigation, it was found that ~60% (27.74 mm) of this displacement was caused by the load deforming (stretching) the thimble (refer to Figure 22). This deforming has no structural impact on the grouted rock anchors and can easily be fixed by replacing the standard thimble with a solid thimble depicted in Figure 23. The other 40% (18.50 mm) is likely due to the stretching of the wire rope tendon which is common and acceptable for displacements of this amount.

Figure 22 - Thimble displacement occurrence during acceptance testing

Figure 23 - Preferred thimble design for future ventures

5.1.5 Improvements to the rock anchor performance test

Due to the limited availability of load cells capable of recording loads up to 100 tonnes. A load cell that did not have a data logger was used. This meant that the data was recorded using a video camera and then processed at a later date. Due to this, it was not noticed until data processing began that there were large gaps in the data owing to errors occurring between the load cell and the display device. These errors averaged ~ 15 seconds but on occasion went on for over 30 seconds. Therefore, it is possible that some peak loads were missed which is likely to influence the maximum loads and average loads.

When conducting future tests like this it is recommended that such a large load cell is unnecessary and that a 30-50 tonne load cell is more appropriate. It is also recommended to use a load cell that records data as processing the data is extremely labour intensive and prone to mistakes without it.

5.2 Provide installation and testing information and methodologies

This section summarises the literature and relevant grouted rock anchor standards to provide forest managers and harvesting contractors with information and sources for information when installing and testing grouted rock anchors.

5.2.1 Installation of Grouted Rock Anchors

Installation of grouted rock anchors is an incredibly vital component of its holding capacity. This section provides information on the preparations and procedures for forest managers and contractors to consider when installing grouted rock anchors.

In general installation costs using a geotechnical company can range from $3 – 15 thousand (North Island) depending on several factors:

- Difficulty of site (setup times, setup equipment),
- Anchor design (length and the diameter of the bore),
- Travel distances.

5.2.1.1 Installation equipment

The installation procedure (section 4.1.1) carried out in this study showcases some of the equipment required for the installation of grouted rock anchors. This mainly included a pneumatic drilling rig and abseiling equipment (refer to Figure 24). For contractors and forest managers wanting to install grouted rock anchors themselves, it is unlikely that they would have access to this equipment and have the correct requirements (tickets) to carry out the installation with this type of drilling rig.

Figure 24 - Pneumatic drilling rig used in the installation process

However, there are other options available. Several New Zealand based companies specialise in the sale of drilling rigs that can be attached to excavators (refer to Figure 25), such as Drill Connex. If a contractor or forest manager intended to use grouted rock anchors throughout their forests, it may be beneficial to invest in such a rig. Using such an attachment would remove the need for abseiling equipment and limit the installation crew size. A roading/landing construction contractor with access to this piece of equipment may be able to drill the hole required during or after landing construction. This option is likely to carry the most upfront costs but if the forest management company is planning to install many anchors it is likely cheaper than hiring a Geotech company. The main limitation of an excavator-based drilling rig is that it is limited to locations where the excavator can reach.

Figure 25 - Example of excavator-based drilling rig

There is also another alternative drilling machine which is hand held rock drills. The HRD100 hydraulic rock drill by Epiroc is an example of a hand held rock drill (refer to Figure 29). A hand held rock drill is cheaper and faster than both a pneumatic drilling rig and an excavator-based rig. It would be used best for smaller grouted rock anchors in places where machines and/or vehicles are unable to reach. Due to the compact size of the machine, there are significant drawbacks to using a handheld rock drill. Firstly, the diameter is significantly limited for handheld rock drills; for the HRD100 the maximum achievable diameter is 42 mm. This is under half of the size of the anchors installed in this report and the anchor design in Figure 11 would certainly be unable to fit. Secondly, the length of the borehole is significantly restricted. Again, referring to the HRD100 the maximum achievable length is 655 mm. There are likely handheld drills with longer lengths but it is highly unlikely they will reach depths of 4 + metres. Finally, unlike the excavator-based drill, handheld drills require previous drilling experience to ensure the borehole is drilled correctly and equipment is not damaged.

Figure 26 - HRD100 Handheld rock drill

The only other necessary equipment is listed below. This equipment is readily available for both contractors and forest managers:

- Rotary or other form of grout mixer,
- Grout pump.

5.2.1.2 Basic Installation processes

The installation process for grouted rock anchors is simple and stays relatively similar even with changes in equipment as expressed above. The process outlined in section 4.1.1, gives a solid foundation for the installation of grouted rock anchors. The following method is a summarised version of the method proposed in section 4.1.1 however, it includes information about grouting conditions and curing times.

1. Site Preparation
    a. Remove hazards and other objects that may hinder the installation process.
    b. Mark positions where the installations will occur.
2. Drilling of bore hole
    a. Setup the preferred mechanism for drilling the borehole.
    b. Begin drilling the hole until the required depth in achieved.
    c. Clean out the borehole if rock mass is stable.
3. Insert tendon
    a. Insert the tendon into the borehole and ensure it is positioned in the centre.
4. Grout the borehole.
    a. Prepare grout ensuring a suitable water:cement ratio (0.34-0.4).
    b. Pump grout into the borehole from the bottom up to ensure no air pockets.
5. Leave grout to cure over a 7 day or longer period before testing or applying load.

5.2.1.3 Installation Considerations

This section covers two key considerations that are essential to grouted rock anchors installation. These two considerations should be examined before the installation process begins.

- **Angle between grouted rock anchor and pull**

Grouted rock anchors are high in tensile strength but are approximately half that in shear strength (Leshchinsky & Russell, 2016). This makes the alignment of the anchor to the guy line incredibly important when trying to maximise holding capacity. Ideally, the bolt should be directly in-line with the direction of the pull. However, this is not always achievable as seen in Figure 13. Therefore, the goal should be to install the grouted rock anchor with the smallest angle possible between itself and the pull direction while also positioning the anchor suitably in the groundmass.

- **The addition of centralizers**

Centralizers are used to ensure that the tendon is inserted and held at the centre of the borehole during installation. The grouted rock anchor needs to be central to the borehole and grout medium to ensure the stress distributions are equally surrounding the anchor. Misaligning the tendon may result in a reduction of the grouted rock anchors holding capacity. Figure 27 depicts a standard centralizer used in New Zealand.

There are also downsides to using such a mechanism. Centralizers have the potential to create small pockets of air throughout the grout medium. This is likely to impact the grouted rock anchors holding capacity and may increase the chance of slippage between the grout/tendon interface. Therefore, it is recommended to not overuse centralizers along the tendon. This may be difficult for wire rope tendons as it is not rigid so more centralizers may be required. There is a process/technique called 'tremie grouting'. This method involves a delivery line for grout being installed with the bar. Then grout is pumped in via this line into the bottom of the hole, with the grout displacing any water etc. that remains in the hole as it rises. Sometimes the delivery line is removed upon completion, other times it is left in the hole; depending on whether it is a temporary or permanent anchor as the delivery line compromises the corrosion proofing in permanent anchors.

Figure 27 - Example of a grouted rock anchor centralizer

5.2.2 General testing information and requirements

This section provides brief testing information that applies to both the sacrificial/investigation and acceptance tests. For more in-depth detail on how to carry out such tests please refer appendix sections 8.1 and 8.2.

Why should a sacrificial/investigation test be undertaken?

The use of a sacrificial or site investigation test is optional and is not required to be undertaken. They are mainly conducted when the ground conditions are unknown, or where prior anchoring experience does not exist. The anchors used in this test are not to be used in the actual structure (i.e., guyline anchors). However, they should still be representative of the anchors which are going to be used, inclination and installation processes should also be the same as the working anchors.

Why should an acceptance test be undertaken?

An acceptance test is conducted to ensure that working anchors at minimum can hold the required design load. For all working grouted rock anchors it is required that before their use, an acceptance test must be conducted.

What is the required testing equipment?

Testing equipment should consist of:

- Stressing/loading device (normally a hydraulic jack)
    - The stressing device needs to have a loading capacity greater or equal to the maximum test load.
    - The extension of the stressing device (jack) should be long enough that the device does not need to be reset during testing.

- Displacement monitoring device
  - The displacement monitoring device should not be connected to the reaction system or stressing device. It should be fixed to a standalone support.
  - The displacement monitoring device must be calibrated within one year of the test.
  - If required a displacement monitoring device may be used on the reaction system to account for excess deformation.
- Load monitoring device
  - The load monitoring device must be calibrated within one year of the test.
- A reaction system
  - The reaction system is required to be able to withstand a force greater or equal to the maximum test load.
  - The reaction system must be designed so that deformation of itself does not occur at the maximum test load.
  - The reaction should not impose stress on the retaining structure greater than the safe bearing capacity.

Contractors or forest managers would likely not be conducting tests themselves due to the complexity of the processes. However, it is important to understand and interrupt the processes and results. Appendix sections 8.1 and 8.2 detail how a contractor or forest manager should present the results of either a sacrificial or acceptance test if it is required.

5.3 Provide grouted rock anchor design information

As discussed in the literature review section, there are several components of grouted rock anchors that can be altered to improve holding capacity and resistance to certain failure modes. This section explores these modifications and presents the reader with realistic options to consider when designing a grouted rock anchor.

After consulting with industry around the prices of grouted rock anchors tendons, the consensus was that $300 per metre is a typical cost. Prices may fluctuate depending on the tendon type (wire rope, rock bolt, and cable bolt), or due to the amount of tendon modifications present.

5.3.1 Type of tendon and tendon diameter

As stated in the literature there are three main types of grouted rock anchor tendons:

- Rock bolts
- Cable bolts
- Wire rope tendons

There is limited research comparing the holding capacities of the three different tendon types. However, choosing one tendon over another is not a concern if the chosen tendon has a greater ultimate breaking strength than the design load. On the contrary, due to the mechanical properties of cable bolts, it is a preferred tendon in embedded lengths over 15 metres. Therefore, any of the three tendons can be used in lengths under 15 m if the ultimate breaking strength is greater than the design load.

The main mechanism to increase a tendon's ultimate breaking strength is to increase its diameter. This effect has already been shown in Table 1. Tendon diameter/ultimate breaking strength is incredibly important to the overall holding capacity of the grouted rock anchor. Hence, without sufficient diameter size and therefore, a low ultimate breaking strength it is meaningless to improve strength through:

- Increasing tendon bond length (embedded length),
- Modifying the shape of the tendon,
- Increase grout strength through the type of grout or hole diameter.

Another way to increase a tendon's ultimate breaking strength, mainly for cable and wire rope tendons, is to use multiple tendons (usually two). The original concept for the tendon used in this study (refer to Figure 30) was a double tendon wire rope anchor. This greatly increased the ultimate breaking strength as the stress is now mobilised over two tendons.

However, due to the increased diameter of the anchor, the second tendon had to be removed as it would not fit in the 100 mm bore hole.

In summary:

- There is little advantage to choosing a different tendon type over another at short embedded lengths if the ultimate breaking strength is greater than the design load.
- Increasing tendon diameter increases tendons' ultimate breaking strength.
- Using a double tendon anchor increases the ultimate breaking strength (wire rope and cable bolt tendons).

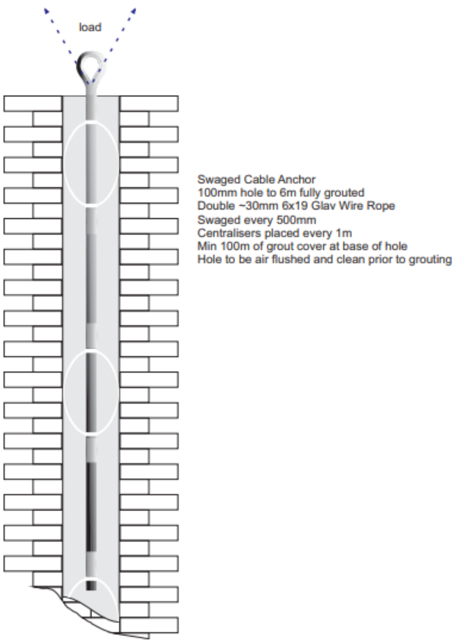

Figure 28 - Original double tendon anchor concept

5.3.2 Length of bonded tendon (embedded length)

The literature review clearly showed that increasing the embedded length of the anchor greatly increased the holding capacity. When the ground conditions and strength of potential grouted rock anchors are unknown, increasing embedded length is an acceptable solution to provide a greater safety factor. This report recommends using a minimum embedded length of five metres.

However, increasing embedded length comes at increased costs. This is due to a longer tendon and more grout being required as well as the possibility of a larger drilling rig being needed.

In summary:

- Increasing the embedded length increases the strength of the anchor.
- Increasing the embedded length increases the costs of the anchor.

5.3.3 Shape of tendon

As discussed in the literature review, the shape of the tendon can have significant effects on the holding capacity of grouted rock anchors:

- For rock bolts common shape modifications are the addition of conical lugs, this is depicted in Figure 31.
- For cable rock bolts a common shape modification is the use of several birdcages along the length, this can be seen below in Figure 32.
- For wire rope tendons modifications are often crimps spaced evenly along the tendon, as seen in Figure 11.

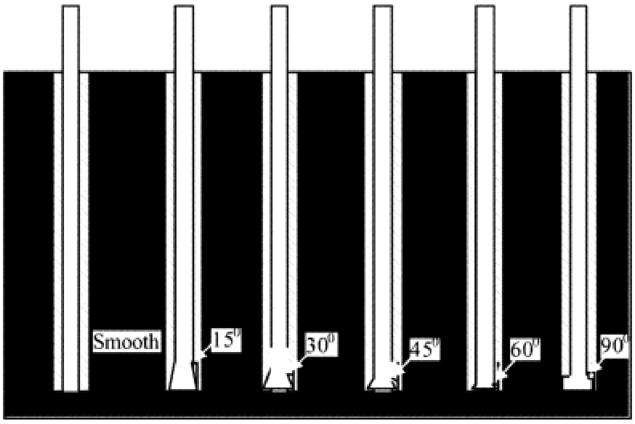

Figure 29 - Example of potential tendon shape modifications

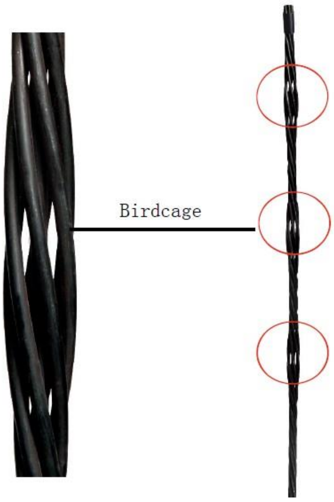

Figure 30 - Example of cable bolt birdcage

The anchors used in this study were modified wire rope anchors with 90-degree crips spaced evenly along the length (refer to Figure 11). This modification was installed to increase the holding capacity of the anchor and reduce the risk of slipping at the tendon/grout interface. Brand new wire rope tends to stretch under significant load and therefore, the diameter shrinks. If the load is sufficient, there is a strong probability that slippage will occur before the ultimate holding capacity is reached. Thus, it is recommended when using wire rope tendons to include crips or similar modifications to reduce the likelihood of spillage at the tendon/grout interface and therefore, premature failure.

It is recommended for both smooth rock bolt tendons to also have some degree of shape modification to increase the shear resistance or add compressive resistance to the tendon/grout interface or use a tendon with ribbing. For cable bolts, birdcages are encouraged if holding capacities are unknown in the area.

In summary:

- Adding modifications to the tendon can increase the holding capacity of the grouted rock anchor.
- Adding modifications likely increases the cost of the anchor.

5.3.4 Grout

Grout properties are an important part of the strengthening mechanisms in a grouted rock anchor due to the shear forces between the grout and tendon and the grout and rock mass. However, for grouted rock anchors used as guy line anchors, general-purpose cement is sufficient with a water-cement ratio between 0.34 and 0.4. The properties of the grout used in this study are shown in Table 8.

The most important part of grout is its installation; it is key that there are no air pockets present when the grout is poured. It is also important to ensure an appropriate curing time for grout. An appropriate curing time for general purpose cement is seven days as seen in Table 10.

Table 8 - Properties of grout used in section 4.3

Brand	CEMIX
Type	General Purpose Cement
Ingredients	Portland Cement, 65997-15-1, > 60% Calcium Carbonate, 13397-26-7, < 10% Gypsum, 13397-24-5, 5%
Application Temperature	5 – 30 degrees Celsius
Strength	34MPa @ 3 days 46.7MPa @ 7 days 63MPa @ 28 days

In summary:

- General purpose cement is sufficient for guyline grouted rock anchors.
- Water-cement ratio of 0.34 to 0.4 is recommended.

5.4 Other applications of grouted rock anchors in forestry operations

Due to the extensive use of grouted rock anchors in the mining and infrastructure industries and knowledge gained from the literature, grouted rock anchors can be applied to several scenarios within forestry operations. This section covers two of these potential scenarios/options.

5.4.1 Supports for Slash Traps

Slash traps are structures designed to catch large pieces of slash or woody debris to stop them from being washed out of a catchment during high flow conditions (Ministry for Primary Industries, 2018).

These high flows are often caused by intense rainfall over an extended period which can mobilise debris including slash, transporting, and depositing it elsewhere. This debris flow can have significant effects on the downstream environment. Visser and Harvey (2020) describe the key elements in designing a slash trap, the flow rate of the waterbody, the structure aperture, the structure placement, the structure's storage capacity, and structure design (strength). Without correctly designing for these components, slash traps can have significant adverse impacts on the environment including, altering the natural alignment of the water body, and creating a weir or inducing scouring of the bed and banks of the water body (Ministry for Primary Industries, 2018).

A venture by a New Zealand forestry company saw the inclusion of grouted rock anchors as supports for a newly designed slash trap. The design of the slash trap is simple, using several rock anchors on each side of the bank which holds a large metal net over the stream. The design and final product can be seen in Figures 30, 31 and 32.

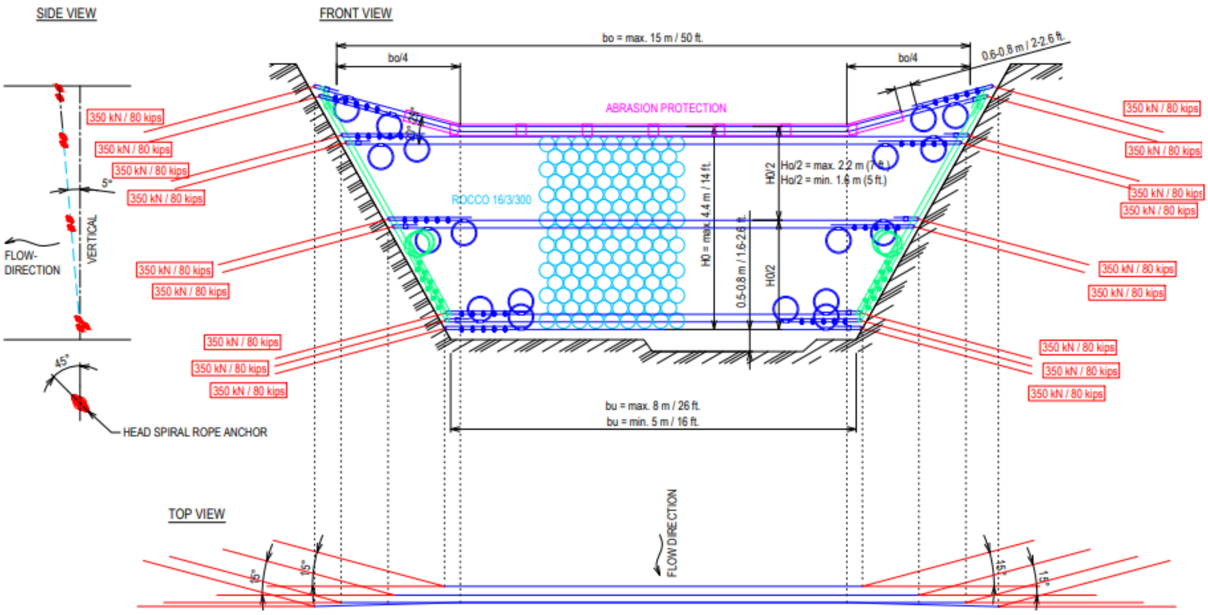

Figure 31 - Design of grouted rock anchor supported slash trap

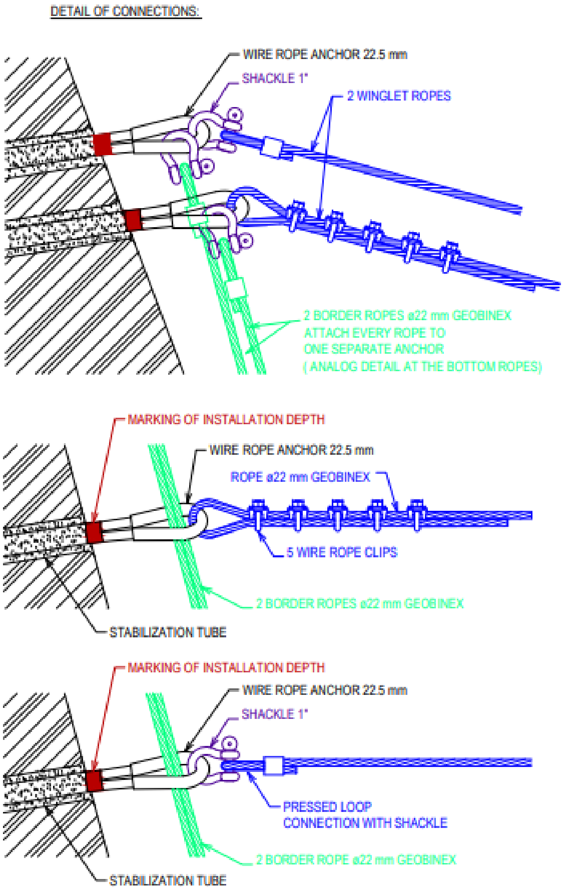

Figure 32 - Design of grouted rock anchor supported slash trap (2)

Figure 33 - Slash trap using grouted rock anchors as supports

This design has several benefits over some of the slash trap designs seen in Visser and Harvey (2020) and Figure 33. Firstly, this design does not change the structure of the riverbank unlike the designs in Figure 33. Hence, there is no impact on the stream bed or fish passage. The design also reinforces the bank due to the presence of multiple grouted rock anchors as the surrounding rock and soil mass are now more stabilised. In future, this slash trap may reduce the chance of bank erosion or complete bank collapse in this area due to the extra stabilisation caused by the grouted rock anchors. Secondly, the structure depicted in Figure 32 compared to structures in Figure 33 requires significantly less material (concrete and steel). Therefore, it can be assumed that the grouted rock anchor supported slash trap is notably cheaper.

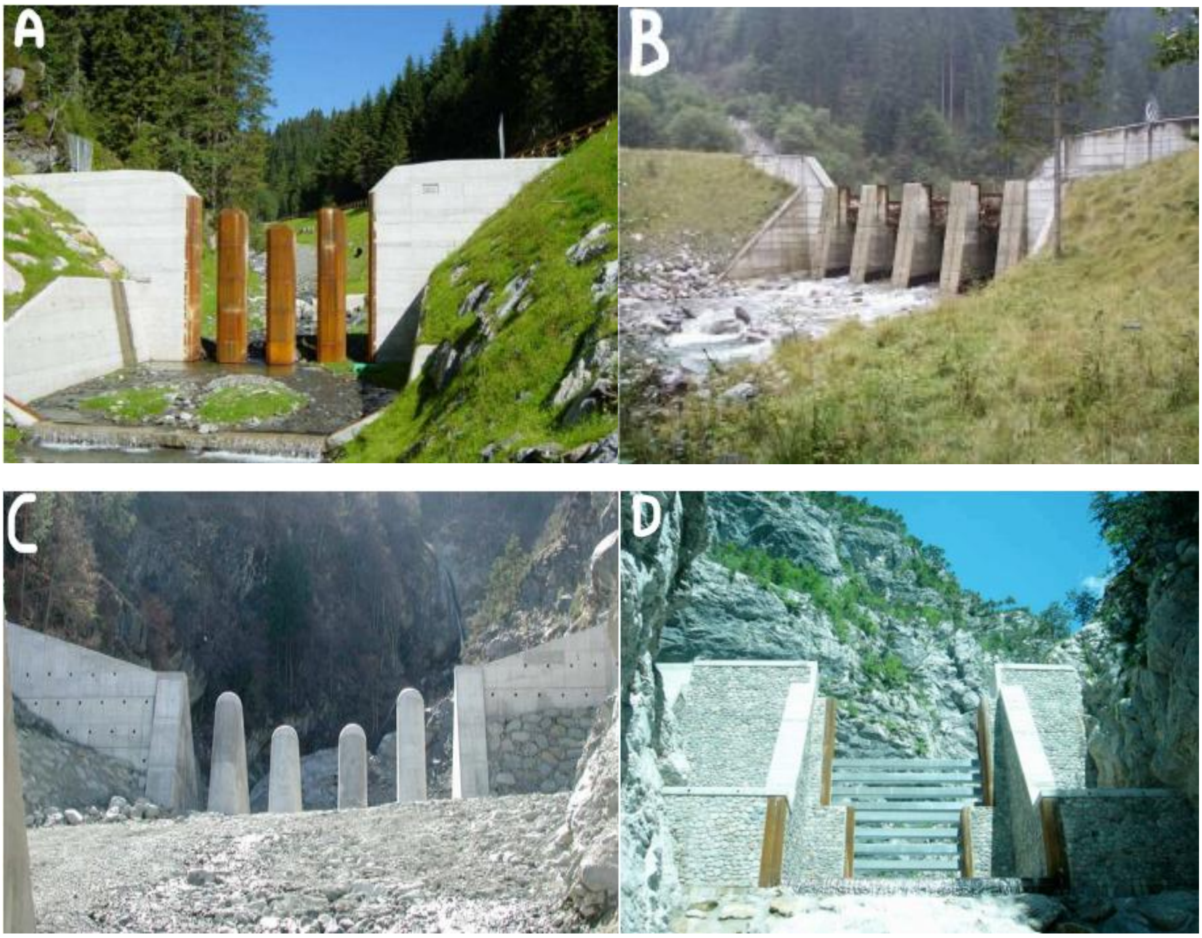

Figure 34 - Examples of slash traps

Though there are many advantages of a grouted rock anchor supported slash trap, there are also disadvantages. Firstly, it is unlikely that the strength of the structure is comparable to the strength of the structures depicted in Figure 33. Therefore, it is likely that in significantly large weather events; a design like Figure 30 would fail in a large stream/river or catchment. Secondly, it is also possible that there would be major damage to the streambank if the rock mass of the bank failed when under load. This may lead to further erosion damage after the failure has occurred. Thirdly, the Figure 30 design cannot be used where the banks of streams/rivers are not of appropriate height or do not contain rock. For example, upstream in Figure 33 A, the bank would not be able to sustain a grouted rock anchor-based design. Finally, it can be assumed that a design like Figure 30 is not appropriate for wide rivers as the likely forces acting on the slash trap will be too great when a significant adverse weather event occurs.

5.4.2 Tailhold Anchors

After exploring the use of grouted rock anchors as guyline anchors for cable logging operations, the opportunity for them to be used as tailholds presents itself. The principle of the tie-down anchors' strength mechanisms and failure modes used in the guyline scenario is the same for this. However, the likely difference between the two would be the size of the loads as tailhold anchors have significantly more load acting on them. Therefore, it is likely that greater strength or more anchors are required to hold the increase in load. By taking into consideration the components in designing grouted rock anchors explored in section 4.1.5 this can be achieved.

Though the processes for a grouted rock anchor tailhold are the same for a guyline, there are several hindrances to incorporating them. Firstly, the location of the tailhold; If the tailhold needs to be in a position where it is difficult for machinery and/or vehicles to access, installation is unlikely. It may be possible to use a hand held rock drill but as discussed in section 5.3.1.1 their depth and diameter are limited. Hence, the strength of a grouted rock anchor using a handheld rock drill is unlikely to be up to standard therefore several may be required. If access was available to machinery, it would be significantly cheaper to use the machine as a tailhold instead. Secondly, unlike mobile tailholds, once grouted rock anchors are installed, they cannot be moved. Hence, becoming useless after that corridor has finished.

Overall, in certain situations, grouted rock anchors may be an appropriate alternative tailholding anchoring system. However, based on the costs and lack of movability (ability to be recycled), their use as tailholds is extremely limited and they cannot compete with mobile or stump tailholds.

5.5 Recommendations to forest managers and contractors

The main goal of this research report was to provide forest managers and contractors with an alternative anchoring system to three main method used. After reviewing the literature and conducting several tests to determine the suitability of grouted rock anchors in these operations, a recommendation has been outlined below

It is recommended to forest managers and contractors that where applicable grouted rock anchors are an appropriate and safe alternative to the current anchoring systems if installed and tested correctly. The main scenarios where these grouted rock anchors can be effective alternatives are listed below. However, these scenarios are dependent on rock being present in the required area:

- Where there is minimal room on the landing for deadmen or mobile anchors. Suitable-sized stumps are also not present.
- Where it is environmentally unfriendly or possesses a significant environmental risk to use deadmen or mobile anchors. Again, suitable-sized stumps are not present.

When considering the use of grouted rock anchors as guyline anchors the following design considerations should be reviewed:

- Type of tendon (rock bolt, cable bolt or wire rope).
- Diameter of the tendon.
- Embedded length.
- Modifications to the shape of the tendon.
- Grout properties.

Testing is also an important part of the use of grouted rock anchors. There are two main tests that apply to guyline grouted rock anchors:

- Acceptance testing: Requirement for working grouted rock anchors. Determines if the anchor can hold the design load.
- Sacrificial/investigation testing: Not required for working grouted rock anchors. Used to determine the potential holding capacity of anchors in locations where no previous anchoring has been conducted or ground conditions are unknown.

For contractors or forest managers looking to expand the use of grouted rock anchors in forestry operations two applications were explored.

Using slash traps with grouted rock anchors as supports (refer to Figure 23) was found to be effective. It is recommended to use to use the design or similar in Figure 23, in situations were:

- The stream/riverbank is rock and of sufficient height.
- The width of the river/stream is medium to small.
- Strengthening of the riverbank is needed.
- Costs and/or carbon footprint is trying to be minimised.

Grouted rock anchor tailholds was a suggested scenario due to the tailhold and guyline mechanisms being similar. It is recommended that when using grouted rock anchors as tailholds to:

- Carry out tension calculations to estimate the loads that would act on the tailhold.
- Design your grouted rock anchor/s to have an acceptable factor of safety on top of the load calculations.

5.6 Limitations and future research

This report has consolidated a significant amount of literature on grouted rock anchors and applied it to forestry operations, in particular guy line anchors. With limited testing, the basis for most of this report is theoretical, though it is backed by extensive research. However, this research has also shown that grouted rock anchors are extremely dynamic and without tests, little can be known about their performance. This issue is more prevalent in forested areas where geotechnical research is often not required. Hence, the main limitation of this research lies in its lack of transferable information from the test site to other sites across the country.

Therefore, it is suggested that for future research the creation of a database of many investigation/sacrificial or acceptance tests from sites across the country should be a focus. This would improve the confidence of forest managers and contractors in grouted rock anchors, lower the cost of the anchor and provide design criteria for anchors in those areas.

Other potential research could include a deeper look at wire rope anchors which are not often present in the current literature, or the effects shock loading may have on the structural integrity of grouted rock anchors.

6 Conclusion

In this study, the use of grouted rock anchors as guylines in cable harvesting operations was assessed through an extensive literature review and two tests. The main goals of the research report were to

The main goals of this research report are outlined below:

- Determine if grouted rock anchors are a suitable alternative anchoring system.
- Provide installation and testing information and methodologies.
- Provide anchor design information.
- Investigate other uses of rock anchors in forestry operations.

The first goal was achieved by installing three grouted rock anchors on the side of a landing in a steep terrain forest and then testing them. The grouted rock anchors then underwent two tests, an acceptance test, and a performance test. The acceptance test was used to determine if the three anchors were able to hold the total design load of 108 tonnes, combined. The results from the tests showed that all three anchors were each able to successfully hold 36 tonnes without any noticeable failure or structural deformation. However, during the test, it was noticed that standard thimbles are prone to severe displacement which affected the test results. Hence, it was noted that for future ventures a solid thimble should be used.

The second test, measuring the anchor performance, was conducted to ensure the anchor was safely able to hold the guyline under working conditions. A 100-tonne load cell measured the loads acting on the grouted rock anchor during operations. The results showed that the maximum load acting on the anchor during a four-day testing period was 20.2 tonnes. This meant the grouted rock anchors had a safety factor of ~ 5:1. Due to the intensive data sorting and errors with the load cell. It was recommended that if a similar test is conducted in future, a smaller load cell with a data logger should be used. It was also noted that during this test, the rigging of the three anchors was incorrectly installed. This meant that the load was unevenly disturbed to the anchors. Therefore, the anchors were no longer compliant with the ACoP, specifically rule 14.1.4.

Overall, it was determined after the two tests that grouted rock anchors are a suitable alternative to the main anchoring systems of guylines. However, this is only true if the design, installation, and testing are done correctly and to the appropriate design loads. Below are the suggested scenarios where rock anchors are likely to be used over the standard anchoring systems:

- Where there is minimal room on the landing for deadmen or mobile anchors. Suitable-sized stumps are also not present.
- Where it is environmentally unfriendly or possesses a significant environmental risk to use deadmen or mobile anchors. Again, suitable-sized stumps are not present.

An installation method was also discussed. Firstly, a simple installation process was proposed which followed the installation method in section 3.3.1 and presented ideas from several grouted rock anchor standards. Secondly, three types of rock drills were evaluated, a pneumatic drilling rig, a drilling rig that attaches to an excavator and a handheld drill. It was found that a pneumatic drilling rig requires abseiling equipment making it difficult for forest managers or contractors to use. The excavator was recommended equipment to use in future, however, it is limited to where the excavator can go. The handheld drill can solve this problem but its diameter and length are limited; hence, more anchors are required. Finally, the angle of installation was discussed. Ensuring the angle between the rock anchor and guyline is minimised is key to the strength of the grouted rock anchors. However, there must be compensation between the angle and where drilling can occur.

Two testing methods were also proposed. The first was a sacrificial/investigation test. This test can be used to assess the ground conditions and holding capacities of grouted rock anchors in locations where previous anchoring has not been conducted or ground conditions are unknown. This test is voluntary but it is recommended to ensure that the design of the working anchor is suitable. The second test was an acceptance test. An acceptance test is used to confirm that the holding capacity of a grouted rock anchor is equal to or greater than the design load. It is required that all working grouted rock anchors undergo an acceptance test before they are used.

An extensive literature review was undertaken to determine which components of grouted rock anchors can be modified to influence their holding capacity. The resulting components are:

- Type of tendon
- Number of tendons (Cable bolt and wire rope anchors only)
- Tendon diameter
- Embedded length
- Shape of tendon
- Grout properties

Finally, two other uses for grouted rock anchors were also explored. The first alternative use was a grouted rock anchor supported slash trap. The design was relatively simple; several grouted rock anchors were installed onto the stream bank, then a large wire rope netting was attached to the anchors. Comparing this slash trap to other designs, it was found that this design likely not only reduces costs and carbon footprint but does not disturb the streambed and prevents major erosion of the streambanks. However, there were also limitations to this design. The design is unlikely to be suitable for larger catchments that have wider water bodies, and the design cannot be used on streams that do not have steep banks.

The second alternative was the use of grouted rock anchors as tailhold anchors. The mechanisms of a tailhold anchor are similar to that of a guyline anchor. However, the loads on the anchor are greater. The report suggested that with the correct anchor design and installation processes, a safe tailhold anchor could be achieved. However, this relied on whether equipment and/or machines had access to the location Although it was stated that if machines can access the location, it is simply cheaper and easier to use a mobile tailhold.

7 References

Bawden, W. F., Hyett, A. J., & Iausch, P. (1992). An experimental procedure for the In Situ testing of cable bolts. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, *29*(5), 525–533.

Belart, F., Leshchinsky, B., & Wimer, J. (2019). Deadman anchoring design for cable logging: a new approach. *Canadian Journal of Forest Research*, 342–357. https://doi.org/10.1139/cjfr-2019-0338

Benmokrane, B., Chennouf, A., & Mitri, H. S. (1995). Laboratory Evaluation of Cement-Based Grouts and Grouted Rock Anchors. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, *32*(7), 633–642. https://d1wqtxts1xzle7.cloudfront.net/50424179/0148-9062_2895_2900021-820161119-30661-1csv3h6-with-cover-page-v2.pdf

Benmorrane, B., Chennouf, A., & Mitri, H. S. (1995). Laboratory Evaluation of Cement-Based Grouts and Grouted rock anchors. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, *32*(7), 633.

Cao, C., Nemcik, J., Aziz, N., & Ren, T. (Eds.). (2019). *Failure modes of rockbolting*. University of Wollongong.

Chen, J., Hagan, P. C., & Saydam, S. (2016). Load Transfer Behavior of Fully Grouted Cable Bolts Reinforced in Weak Rocks Under Tensile Loading Conditions. *Geotechnical Testing Journal*, *39*(2), 20150096. https://doi.org/10.1520/gtj20150096

Chen, J., Hagan, P. C., & Saydam, S. (2017). Sample diameter effect on bonding capacity of fully grouted cable bolts. *Tunnelling and Underground Space Technology*, *68*, 238–243. https://doi.org/10.1016/j.tust.2017.06.004

Chen, J., Liu, P., Zhao, H., Zhang, C., & Zhang, J. (2021). Analytical studying the axial performance of fully encapsulated rock bolts. *Engineering Failure Analysis*, *128*, 105580. https://doi.org/10.1016/j.engfailanal.2021.105580

Chen, J., Saydam, S., & Hagan, P. C. (2015). An analytical model of the load transfer behavior of fully grouted cable bolts. *Construction and Building Materials*, *101*, 1006–1015. https://doi.org/10.1016/j.conbuildmat.2015.10.099

Chen, J., Saydam, S., & Hagan, P. C. (2018). Numerical simulation of the pull-out behaviour of fully grouted cable bolts. *Construction and Building Materials*, *191*, 1148–1158. https://doi.org/10.1016/j.conbuildmat.2018.10.083

Chen, J., Zhao, H., He, F., Zhang, J., & Tao, K. (2021a). Studying the performance of fully encapsulated rock bolts with modified structural elements. *International Journal of Coal Science &Amp; Technology*, *8*(1), 64–76. https://doi.org/10.1007/s40789-020-00388-z

Chen, J., Zhao, H., He, F., Zhang, J., & Tao, K. (2021b, January 4). Studying the performance of fully encapsulated rock bolts with modified structural elements. *International Journal of Coal Science &Amp; Technology*, *8*(1), 64–76. https://doi.org/10.1007/s40789-020-00388-z

FITEC. (2005, January). *Best practice guidelines for cable logging* (No. 2). https://safetree.nz/wp-content/uploads/2015/02/Cable-Logging.pdf

Fraser, D., & Robinson, D. (1998). *Excavator Mobile Anchoring Methods* (No. 4). Liro Limited.

Hartsough, B. R., Drews, E., Miles, J. A., Mehlschau, J. J., & Vannucci, B. (1992). Preliminary experiences with cable logging anchors for rocky soils. *Transactions of the ASAE*, *35*(6), 1995–1999.

Hartsough, B. R., Visser, R. J. M., Miles, J. A., & Drews, E. S. (1997). Improved Cable logging Anchors for Rocky Soils. *American Society of Agricultural Engineers* , *40*(2), 261–266.

Hyett, A. J., Bawden, W. F., Macsporran, G. R., & Moosavi, M. (1995). A Constitutive Law for Bond Failure of Fully-grouted Cable Bolts Using a Modified Hoek Cell. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, *32*(1), 11–36.

Hyett, A. J., Moosavi, M., & Bawden, W. F. (1996). Load distribution along fully grouted bolts, with emphasis on cable bolt reinforcement. *International Journal for Numerical and Analytical Methods in Geomechanics*, *20,* 517–544.

Jahangir, E., Blanco-Martín, L., Hadj-Hassen, F., & Tijani, M. (2021). Development and application of an interface constitutive model for fully grouted rock-bolts and cable-bolts. *Journal of Rock Mechanics and Geotechnical Engineering*, *13*(4), 811–819. https://doi.org/10.1016/j.jrmge.2021.03.011

Karanam, U. M. R., & Dasyapu, S. K. (2005). Experimental and numerical investigations of stresses in a fully grouted rock bolts. *Geotechnical and Geological Engineering*, *23*(3), 297–308. https://doi.org/10.1007/s10706-004-9518-x

Kilic, A., Yasar, E., & Celik, A. G. (2002). Effect of grout properties on the pull-out load capacity of fully grouted rock bolt. *Tunnelling and Underground Space Technology*, *17*, 355–462. https://www.researchgate.net/profile/Ergul-Yasar/publication/222224152_Effect_of_grout_properties_on_the_pull-out_load_capacity_of_fully_grouted_rock_bolt/links/5cb5729fa6fdcc1d4997adf8/Effect-of-grout-properties-on-the-pull-out-load-capacity-of-fully-grouted-rock-bolt.pdf

Kılıc, A., Yasar, E., & Atis, C. (2003). Effect of bar shape on the pull-out capacity of fully-grouted rockbolts. *Tunnelling and Underground Space Technology*, *18*(1), 1–6. https://doi.org/10.1016/s0886-7798(02)00077-9

Leshchinsky, B., & Russell, M. L. (2016, October). *Mobile Anchors for Cable Yarding Systems*. Oregon State University.

Leshchinsky, B., Sessions, J., & Wimer, J. (2015). Analytical design for mobile anchor systems. *International Journal of Forest Engineering*, *26*(1), 10–23. https://doi.org/10.1080/14942119.2015.1023014

Li, D., Cai, M., & Masoumi, H. (2021). A constitutive model for modified cable bolts exhibiting cone shaped failure mode. *International Journal of Rock Mechanics and Mining Sciences*, *145*, 104855. https://doi.org/10.1016/j.ijrmms.2021.104855

Li, D., Masoumi, H., Saydam, S., & Hagan, P. C. (2017). A constitutive model for load-displacement performance of modified cable bolts. *Tunnelling and Underground Space Technology*, *68*, 95–105. https://doi.org/10.1016/j.tust.2017.05.025

Li, D., Masoumi, H., Saydam, S., Hagan, P. C., & Asadizadeh, M. (2019). Parametric study of fully grouted cable bolts subjected to axial loading. *Canadian Geotechnical Journal*, *56*(10), 1514–1525. https://doi.org/10.1139/cgj-2018-0470

Li, X., Aziz, N., Mirzaghorbanali, A., & Nemcik, J. (2017). Comparison of the shear test results of a cable bolt on three laboratory test apparatuses. *Tunnelling and Underground Space Technology*, *61*, 82–89. https://doi.org/10.1016/j.tust.2016.10.003

Li, X., Nemcik, J., Mirzaghorbanali, A., Aziz, N., & Rasekh, H. (2015a). Analytical model of shear behaviour of a fully grouted cable bolt subjected to shearing. *International Journal of Rock Mechanics and Mining Sciences*, *80*, 31–39. https://doi.org/10.1016/j.ijrmms.2015.09.005

Li, X., Nemcik, J., Mirzaghorbanali, A., Aziz, N., & Rasekh, H. (2015b). Analytical model of shear behaviour of a fully grouted cable bolt subjected to shearing. *International Journal of Rock Mechanics and Mining Sciences*, *80*, 31–39. https://doi.org/10.1016/j.ijrmms.2015.09.005

Li, X., Yang, G., Nemcik, J., Mirzaghorbanali, A., & Aziz, N. (2019). Numerical investigation of the shear behaviour of a cable bolt in single shear test. *Tunnelling and Underground Space Technology*, *84*, 227–236. https://doi.org/10.1016/j.tust.2018.11.016

Ma, S., Nemcik, J., & Aziz, N. (2013). An analytical model of fully grouted rock bolts subjected to tensile load. *Construction and Building Materials*, *49*, 519–526. https://doi.org/10.1016/j.conbuildmat.2013.08.084

Ma, S., Nemcik, J., Aziz, N., & Zhang, Z. (2014). Analytical model for rock bolts reaching free end slip. *Construction and Building Materials*, *57*, 30–37. https://doi.org/10.1016/j.conbuildmat.2014.01.057

Madenga, V., Zou, D., & Zhang, C. (2006). Effects of curing time and frequency on ultrasonic wave velocity in grouted rock bolts. *Journal of Applied Geophysics*, *59*(1), 79–87. https://doi.org/10.1016/j.jappgeo.2005.08.001

Mancuso, A., Belart, F., Leshchinsky, B., Russell, M. L., & Kiser, J. D. (2018). Behavior and assessment of mobile anchors in cable yarding systems. *Canadian Journal of Forest Research*, *48*(11), 1382–1387. https://doi.org/10.1139/cjfr-2018-0269

Ministry for Primary Industries. (2018, April). NESPF Guidance - Slash traps. In *Ministry for Primary Industries* (No. V1). Retrieved August 29, 2022, from https://www.mpi.govt.nz/dmsdocument/28566-NESPF-Guidance-slash-traps#:~:text=Slash%20or%20debris%20traps%20are,behind%20after%20plantation%20forestry%20activities'.

Ministry of Business, Innovation and Employment. (2012, December). *Approved Code of Practice for Safety and Health in Forest Operations*. Ministry of Business, Innovation & Employment. https://www.worksafe.govt.nz/topic-and-industry/forestry/safety-and-health-in-forest-operations/

Moosavi, M., Bawden, W. F., & Hyett, A. J. (2002). Mechanism of bond failure and load distribution along fully grouted cable-bolts. *Mining Technology*, *111*(1), 1–12. https://doi.org/10.1179/mnt.2002.111.1.1

Rajaie, H. (1990, June). *Experimental And Numerical Investigations Of Cable Bolt Support Systems*. https://escholarship.mcgill.ca/concern/theses/3t945r493

Sabatini, P. J., Pass, D. G., & Bachus, R. C. (1999, June). *Geotechnical Engineering Circular No.4 - Ground Anchors and Anchored Systems* (FHWA-IF-99-015). Federal Highway Administration.

Schroeder, W. L., & Swanston, D. N. (1992, April). *Installation and Use of Epoxy-Grouted Rock Anchors for Skyline logging in southeast Alaska*. United States Department of Agriculture .

Shu, S., Muhunthan, B., Badger, T. C., & Grandorff, R. (2005). Load testing of anchors for wire mesh and cable net rockfall slope protection systems. *Engineering Geology*, *79*(3–4), 162–176. https://doi.org/10.1016/j.enggeo.2005.01.008

Smith, J. E., & Stalcup, J. V. (1966, April). *Deadman anchorages in various soil mediums* (R-434). U. S. Naval civil engineering laboratory. https://apps.dtic.mil/sti/pdfs/AD0631848.pdf

Smith, J., & McMahon, S. (1995). *Stump anchorage capacity on two contrasting soil types* (No. 22). LIRO Limited.

Stoupa, J. (1984, July). *Behavior and Load Carrying Capacity of Stump Anchors*. Oregon State University.

Tahmasebinia, F., Zhang, C., Canbulat, I., Vardar, O., & Saydam, S. (2018). Numerical and analytical simulation of the structural behaviour of fully grouted cable bolts under impulsive loading. *International Journal of Mining Science and Technology*, *28*(5), 807–811. https://doi.org/10.1016/j.ijmst.2018.08.012

Thenevin, I., Blanco-Martín, L., Hadj-Hassen, F., Schleifer, J., Lubosik, Z., & Wrana, A. (2017). Laboratory pull-out tests on fully grouted rock bolts and cable bolts: Results and lessons learned. *Journal of Rock Mechanics and Geotechnical Engineering*, *9*(5), 843–855. https://doi.org/10.1016/j.jrmge.2017.04.005

Wu, S., Chen, H., Lamei Ramandi, H., Hagan, P. C., Hebblewhite, B., Crosky, A., & Saydam, S. (2018). Investigation of cable bolts for stress corrosion cracking failure. *Construction and Building Materials*, *187*, 1224–1231. https://doi.org/10.1016/j.conbuildmat.2018.08.066

Yazici, S., & Kaiser, P. K. (1992). Bond strength of grouted cable bolts. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, *29*(3), 279–292.

8 Appendices

8.1 Sacrificial or investigation Testing

The sacrificial or investigation testing information and procedures provided in this report are based on EN ISO 22477-5 (Method 1) and advice from a geotechnical expert.

Before conducting the test, the following procedures should be followed:

- Establish a maximum test load (P_p). For guy line rock anchors this datum load should be 120% of the mainlines strength or split amongst however many anchors are installed.
- Establish a datum load (P_a). This is used to minimise the effects of the test setup moving during initial loading. Usually, the datum load is 10% of the P_p.
- Check measuring equipment is safe and functional. Ensure the displacement reference system is located where it is unaffected by the testing system or the climate.
- Set up the loading/stressing system and ensure it is on the same axis as the anchor.

For this test, the grouted rock anchors are loaded in cycles. Cycles can range from a minimum of six to upwards of ten depending on the load. Each cycle has a specific maximum load which is a percentage of the maximum test load (P_p). An example of this loading cycle can be seen in Table 11.

Table 9 - Example of sacrificial anchor test loading cycles

Cycle #	% of (P_p)	Load (kN)
1	40	80
2	55	110
3	70	140
4	90	180
5	100	200
6	120	240

Note: An example P_p of 200 kN was used in this case

Table 12 gives an example of a recording sheet needed for the test and the loading steps required. The highlighted cells show which displacement measurements should be taken for each load.

Table 10 - Example of a datasheet for sacrificial/investigation anchoring testing

Applied test load				**Displacement measurements**				
% of P_p	**Load (kN)**	**Load (t)**	**Load (PSI)**	**Initial**	**1 Minutes**	**5 Minutes**	**10 Minutes**	**15 Minutes**
Cycle 1								
10%	20	2.04						
20%	40	4.08						
30%	60	6.12						
40%	80	8.16						
30%	60	6.12						
20%	40	4.08						
10%	20	2.04						
Cycle 2								
10%	20	2.04						
25%	50	5.10						
40%	80	8.16						
55%	110	11.22						

40%	80	8.16						
25%	50	5.10						
10%	20	2.04						
Cycle 3								
10%	20	2.04						
40%	80	8.16						
60%	120	12.24						
70%	140	14.28						
60%	120	12.24						
40%	80	8.16						
10%	20	2.04						
Cycle 4								
10%	20	2.04						
50%	100	10.20						
70%	140	14.28						
90%	180	18.35						
70%	140	14.28						
50%	100	10.20						
10%	20	2.04						
Cycle 5								
10%	20	2.04						
50%	100	10.20						
80%	160	16.32						
100%	200	20.39						
80%	160	16.32						
50%	100	10.20						
10%	20	2.04						
Cycle 6								
10%	20	2.04						
70%	140	14.28						
100%	200	20.39						
120%	240	24.47						
100%	200	20.39						
70%	140	14.28						
10%	20	2.04						

The data from the test should be presented in the following graphs.:

- Graph of displacement versus anchor load at each cycle peak (Figure 35),

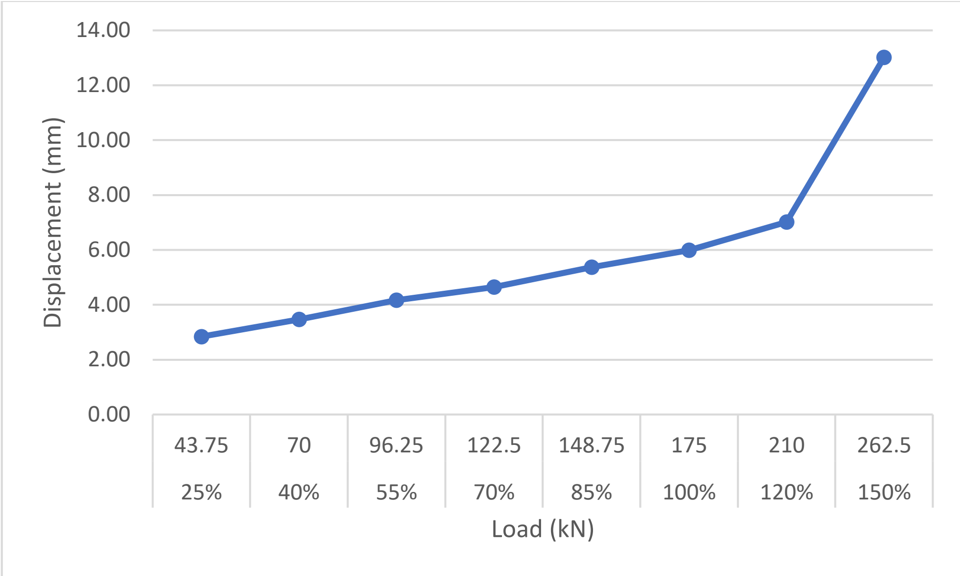

Figure 35 - Example of displacement versus anchor load graph

– Graph of displacement versus time at each cycle peak (Figure 36),

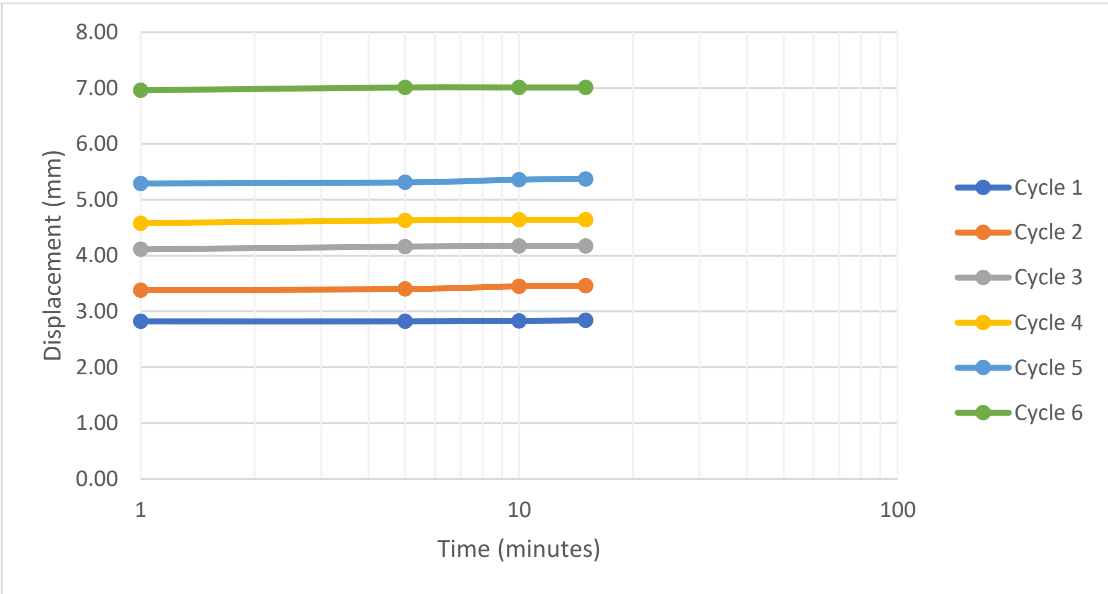

Figure 36 - Example of a displacement at maximum load for a cycle versus time

– Graph of α_1 (creep ratio) versus anchor load (Figure 37) (If necessary),

The creep ratio is defined by the equation below,

$$\alpha_1 = (s_b - s_a)/\log\left(\frac{t_b}{t_a}\right)$$

s_a = displacement of the anchor head at the time t_a

s_b = displacement of the anchor head at the time t_b

t_a = start of the respective time interval

t_b = end of the respective time interval

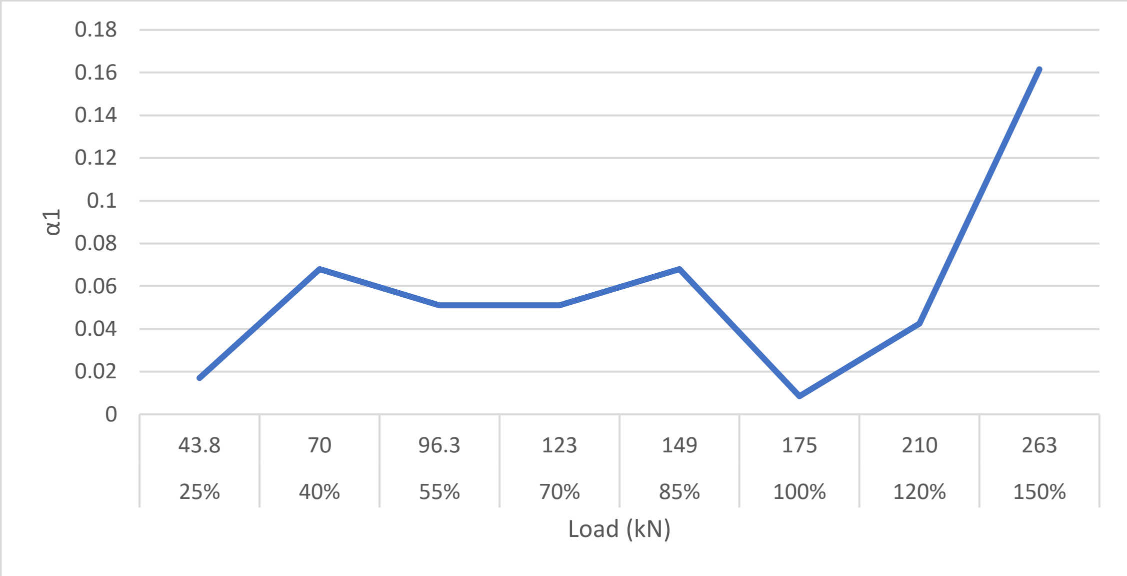

Figure 37 - Example of creep ratio versus anchor load graph

– Graph of displacement versus load cycles (Figure 38) (If necessary).

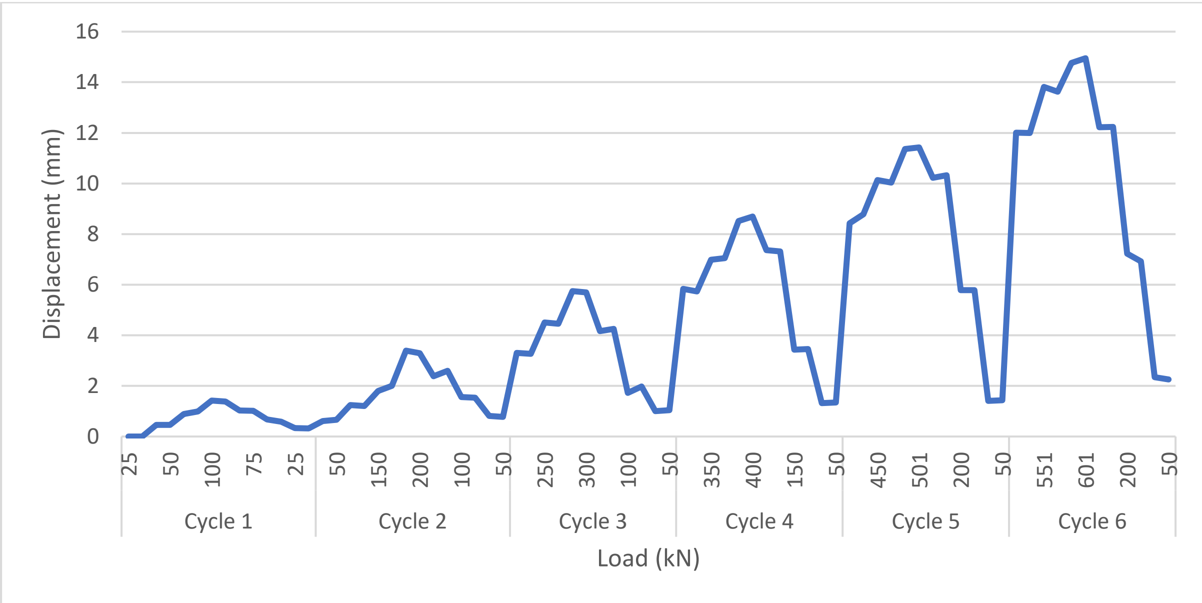

Figure 38 - Example of displacement versus load cycles

The data from the test can also be used to calculate the following:

– Anchor pull-out resistance, R_a

Anchor pull-out resistance is determined in two ways. Either the anchor pull-out resistance is reached when the creep ratio (α_1) exceeds 2.00 mm or if the creep ratio (α_1) does not reach 2.00 mm the anchor pull-out resistance is equal to the maximum test load.

NOTE: For a more in-depth guide please refer to British Standard EN ISO 24477-5 & BS:8081-2015

8.2 Acceptance test

The acceptance testing information and procedures provided in this report are based on EN ISO 22477-5 (Method 1), advice from a geotechnical expert and the process used for the tests conducted in this report.

Prior to conducting the test, the following procedures should be followed:

- Establish a maximum test load/proof load (P_p). For guy line rock anchors this datum load should be 120% of the mainlines strength or split amongst however many anchors are installed.
- Establish a datum load (P_a). This is used to minimise the effects of the test setup moving during initial loading. Usually, the datum load is 10% of the P_p.
- Check measuring equipment is safe and functional. Ensure the displacement reference system is located where it is unaffected by the testing system or the climate.
- Set up the loading/stressing system and ensure it is on the same axis as the anchor.

For an acceptance test, the loading should occur with a minimum of five steps. When moving from one step to another the load should not be applied faster than ten kN per second, this is the same for when descending steps. An example of a recording sheet has been provided in Table 13.

Table 11 - Example of acceptance testing recording sheet

Applied test load			Displacement measurements						
% of Proof load	Load (kN)	Load (PSI)	Initial	1 minute	2 minutes	5 minutes	10 minutes	15 minutes	20 minutes
Alignment	10								
20%	60								
40%	120								
60%	180								
80%	240								
100%	300								
120%	360								
100%	300								
60%	180								
20%	60								

The data from acceptance tests should be presented in the follow:

- Graph of displacement versus anchor load (Figure 39),

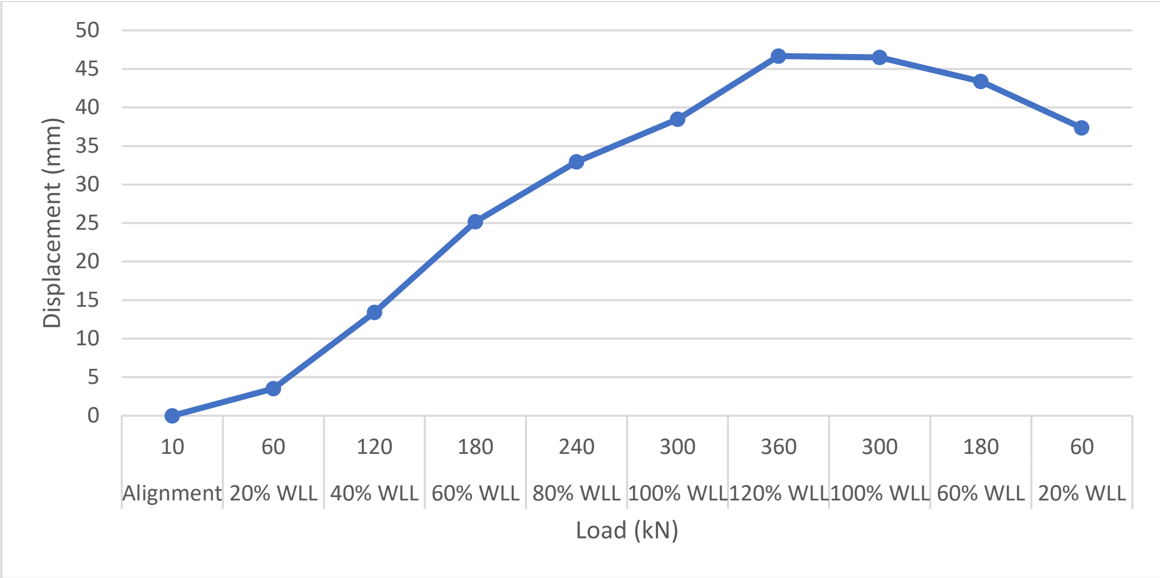

Figure 39 - Example of a displacement versus anchor load graph

– Graph of displacement versus time (Figure 40)

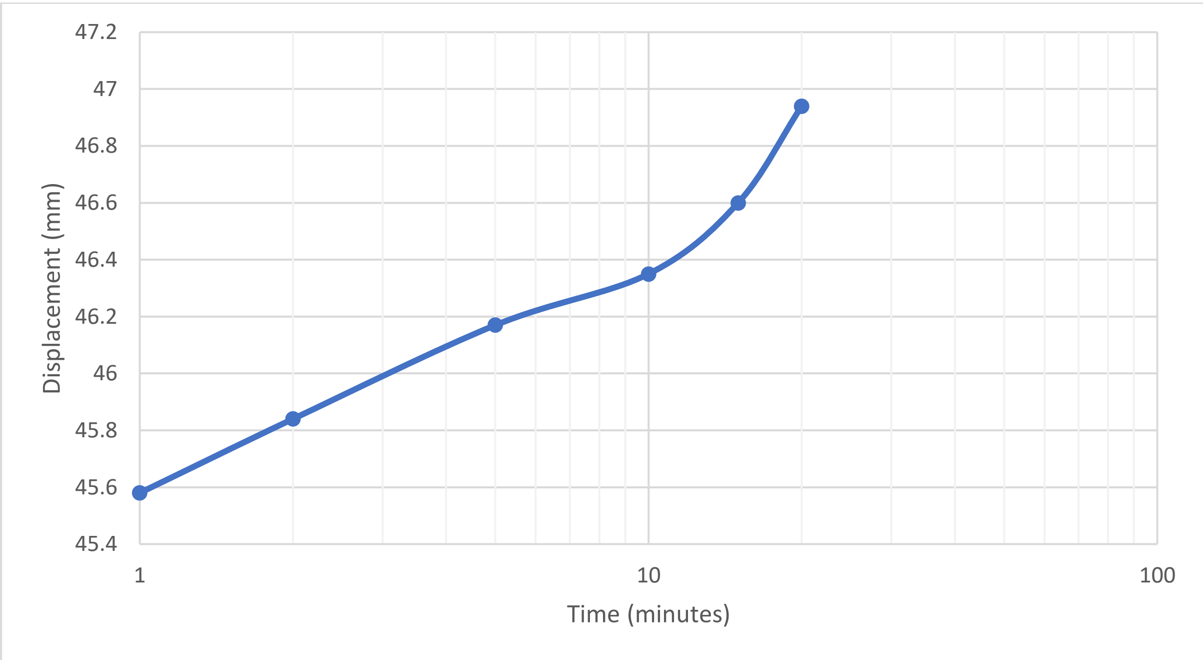

Figure 40 - Example of a displacement versus time graph

The following should also be calculated:

– Total anchor displacement at proof load.
– Creep ratio (α_1) at proof load (if necessary) (refer to the equation for α_1 in section 8.1).

NOTE: For a more in-depth guide please refer to British Standard EN ISO 24477-5 & BS:8081-2015