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An analysis of sacrificial anchor tests and geological conditions across the NCTIR project

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ABSTRACT

The Magnitude (M_w) 7.8 Kaikōura earthquake struck the east coast of the South Island of New Zealand in November 2016, resulting in widespread damage to the slopes along the Kaikōura coast. Many of the subsequent remediation measures relied on rock anchors, and a significant amount of test data from these anchors was collected. This paper provides a summary of the geological conditions and analysis of the sacrificial anchor test results from the various slope stabilisation systems installed. The geological conditions encountered are compared with the adopted grout to ground bond stresses to highlight trends and provide an insight into the strength of the different geological conditions for use in design. This may be useful in other areas of similar geology in the future. This analysis provides a link between the engineering geologists' site investigations and the geotechnical engineers' designs.

1 INTRODUCTION

The 2016 Magnitude (M_w) 7.8 Kaikōura Earthquake devastated road and rail infrastructure over hundreds of kilometres and resulted in over a billion dollars in damage. The Waka Kotahi Transport Agency (Waka Kotahi) and KiwiRail established the North Canterbury Transport Infrastructure Recovery (NCTIR) Alliance with the goal of re-opening the road and rail networks by December 2017.

As part of the NCTIR programme, more than 85 landslides have been remediated. Each landslide created a unique complex hazard, and required mitigation measures to reduce the risk to the road and rail users. These mitigation measures included many ground and rock anchors within the protection systems and structures.

The intent of this paper is to provide an insight into the geological conditions and sacrificial anchor test results at multiple NCTIR sites around Kaikōura. The geological units encountered during drilling are compared with the grout-to-ground bond stresses gained from sacrificial testing to highlight trends and provide an insight for use in the design process. The data presented may be useful in other areas of similar geology.

2 GEOLOGY

The Kaikōura Coast is dominated by the north-east trending Seaward Kaikōura Range. The slopes rise from the sea along the coastline, and the transport corridor is located on a narrow width of flat land between the foreshore and the toe of the hillslopes. The steep and rugged slopes adjacent to the corridor rise to over 300 m above sea level. Slope angles are typically 35° to 50°, with localised short sections of near-vertical cliffs along the coastline.

Basement 'Greywacke' of the Pahau Terrane forms the hills along the coast south of Kaikōura and much of the North Kaikōura Coast. The Greywacke typically comprises slightly to moderately weathered sandstone and mudstone (argillite), often with a mantle of moderately to highly weathered rock close to the ground surface. The mudstone is typically weak and the sandstone is moderately strong to strong. Within the southern Seaward Kaikōura region, the Greywacke has sub-parallel strata with widespread steeply dipping joints and occasional larger hinge fold features.

Colluvium, and in some cases recent earthquake-induced deposits of talus, overlies the Greywacke and is typically a mixture of rock fragments, silt and sand. The colluvium is widely distributed over the basement rock throughout the project area where slope angles are gentler than 45°. The colluvial mantle is typically 0.5 m to 1 m thick near the ridge tops, and increases in thickness downslope, with a maximum observed thickness of approximately 15 m.

The main geological units in the Kaikōura region are shown in Figure 1, below, overlaid with the locations of the southern project sites considered in this study.

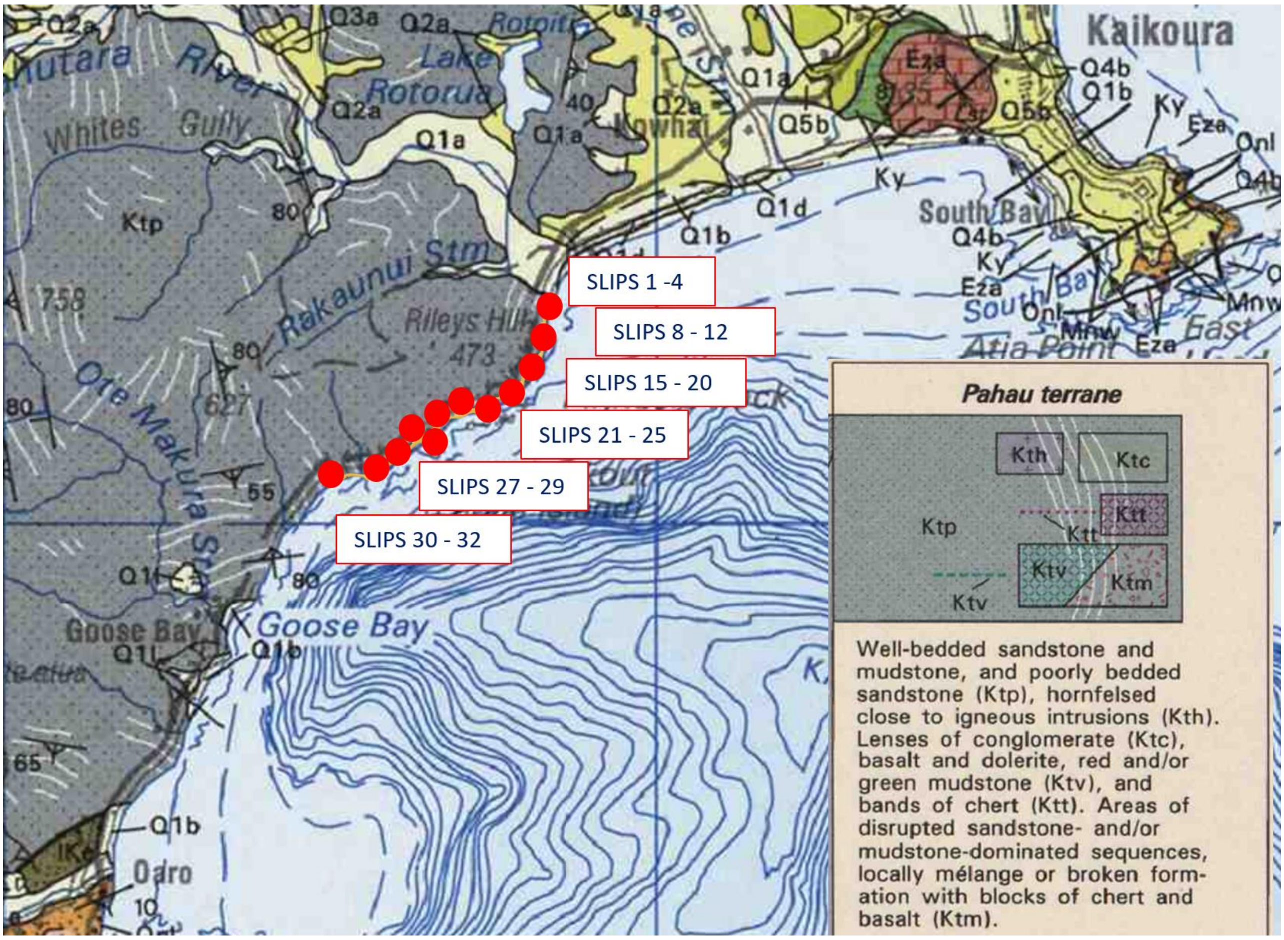


Figure 1: Geological mapping of the Kaikōura area from Rattenbury, Townsend and Johnson (2006) overlaid with project testing sites in the southern Kaikōura region considered in this study.

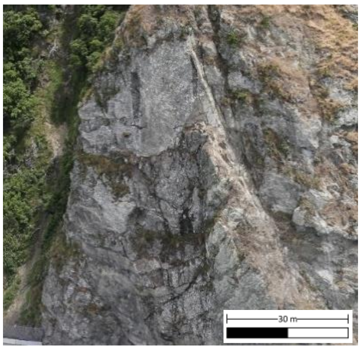
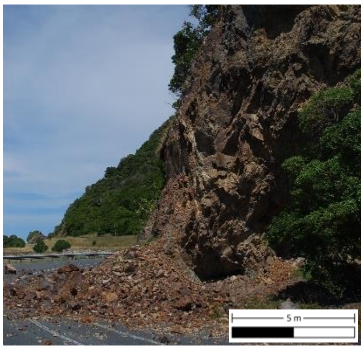
2.1 NCTIR Rock Mass Classification

Due to the variety of geological characteristics within Greywacke in the Kaikōura region, Macfarlane and Justice (2017) introduced a classification system for the rock masses across the NCTIR project. The NCTIR Rock Mass Classification system, outlined below in Table 1, is based on the Geological Strength Index, GSI (Hoek et al., 2002) and was developed specifically for the assessment of slopes within the Greywacke and Greywacke-derived colluvium. The classification system was developed to assist with the consistency of recognising and defining the geological site conditions observed at the surface to improve inputs during design.

The classification system has four classes (Class I – IV) to cover the range of Greywacke material, from a defect controlled competent rock mass (Class I), to colluvium/talus (Class IV). All of the rock classes can be found across the coast. The majority of Class I rock south of Kaikōura has been encountered at the larger vertical cliffs at truncated spurs above the road platform. The Class II and some Class III were generally encountered within the upper outcropping rock along ridgelines, where topographical amplification has resulted in significant shaking damage following the Kaikōura Earthquake. Class III and Class IV were encountered within the inter-joining slopes and locations of remnant paleolandslides, and by total area form the majority of surface geology along the southern extent of the NCTIR project sites.

The characteristics of each geological classification resulted in different set-ups for anchor testing, which is shown in Table 1, and discussed further in Section 4.

Table 1: NCTIR Rock Mass Classification with Project Examples.

Class	Geological Description *(Macfarlane & Justice 2017)*	Anchor Installation Method	Example Project Sites *(approximate scale)*	Corresponding Anchor Testing
I	*Stability controlled by persistent defects (wedges, plane failures, topple)*	Majority open-hole drilled, gravity grouted		
II	*Failure **may be** governed by defects (broken/dilated rock slides off underlying less disturbed/less realxed rock) or **may be** governed by rock mass strength.*	Mostly open-hole drilled, gravity grouted, with grout-flushed self-drillers used in some locations		

III	*Failure governed by rock mass strength.*	Mostly grout-flushed self-drilling anchors, but some open-hole drilled anchors.		
IV	*Colluvium/landslide debris/talus. Inherently unstable if oversteepened (undercut); erodible under moderate to high precipitation.*	Majority grout flush self-drilling anchors		

3 SACRIFICIAL ANCHORS

Anchors were installed as part of anchored meshes, rockfall protection fences and debris flow barriers. Anchor types included galvanised solid steel bars installed using open-hole drilling in competent rock, and galvanised-epoxy coated hollow-bar self-drilling anchors used in the weaker rock mass and colluvium, where the risk of hole collapse was apparent.

Sacrificial anchors were installed to confirm the grout to ground bond strengths used in design at the specific location of the structure or within similar geology. The sacrificial anchors were generally installed to a total length of 3 m, with a 1.5 m un-bonded length and 1.5 m bonded lengths, see Figure 2. The drill diameter and installation methodology generally were the same as for production anchors, expect that grout was only installed in the bonded length.

The anchor installation method, as outlined in Table 1, is influenced by the rock mass classification. The installation method used, along with the rock mass characteristics, has an impact on the total size of the grout column, with some self-drilling anchors recorded using grout volumes up to 300% of the theoretical hole volume. The grout columns have been considered equal across rock masses during analysis (i.e. 100% of the theoretical drilled hole) but realistically self-drilling anchors and open-hole anchors in weaker rock masses will have larger grout columns and therefore will return apparent bond pressures higher than reality due to the larger surface area. This why the installation method is kept consistent between sacrificial and design anchors.

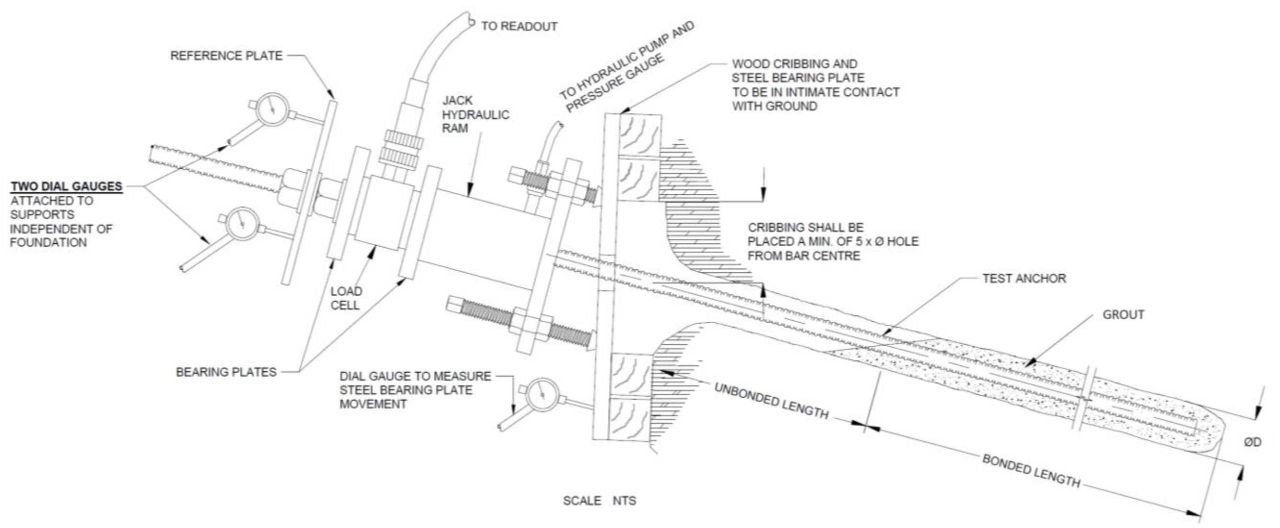


Figure 2: NCTIR standard detail for sacrificial anchor installation and testing.

At the start of the NCTIR project the grout to ground bond strengths used in design relied upon the NCTIR Rock Mass Classification determined in the field by the project geologists, and the various empirical ranges provided in the literature, such as Ostermayer and Barley (2002) and Littlejohn and Bruce (1977).

However, as the NCTIR project progressed, a significant number of sacrificial anchor tests were completed and the results began to be compiled into a single dataset. The site location, anchor type, bonded and unbonded lengths, failure load, drillers' notes and the NCTIR Rockmass Classification were all recorded. Using this consolidated dataset, the team were able to analyse the grout to ground bond strengths in relation to the NCTIR Rock Mass Classification and provide more accurate estimations of bond strengths based on the surface geology.

4 ANALYSIS OF THE RESULTS

The analysis of the sacrificial anchor data is considered in two parts: observations and predictions.

4.1 Part 1: Observed Values

The highest, lowest and mean values from the sacrificial anchor test results are shown in Figure 3 for each class of rock. The mean bond strengths for Classes I to IV are 1040kPa, 650kPa, 440kPa and 300kPa, respectively.

The volume of tests completed within each rock mass classification is also shown in Figure 3. The high volume of Class IV testing data is considered a consequence of two factors:

1. The majority of structures, and thus sacrificial anchor tests, were installed in the colluvium at the toe of failed slopes where protection structures were needed.
2. There is a relatively simple distinction between rock (Class I, II, III) and colluvium (Class IV), and the overlap between Classes I-III (i.e. rocks that fall into Class I/II and II/III) spreads these results out.

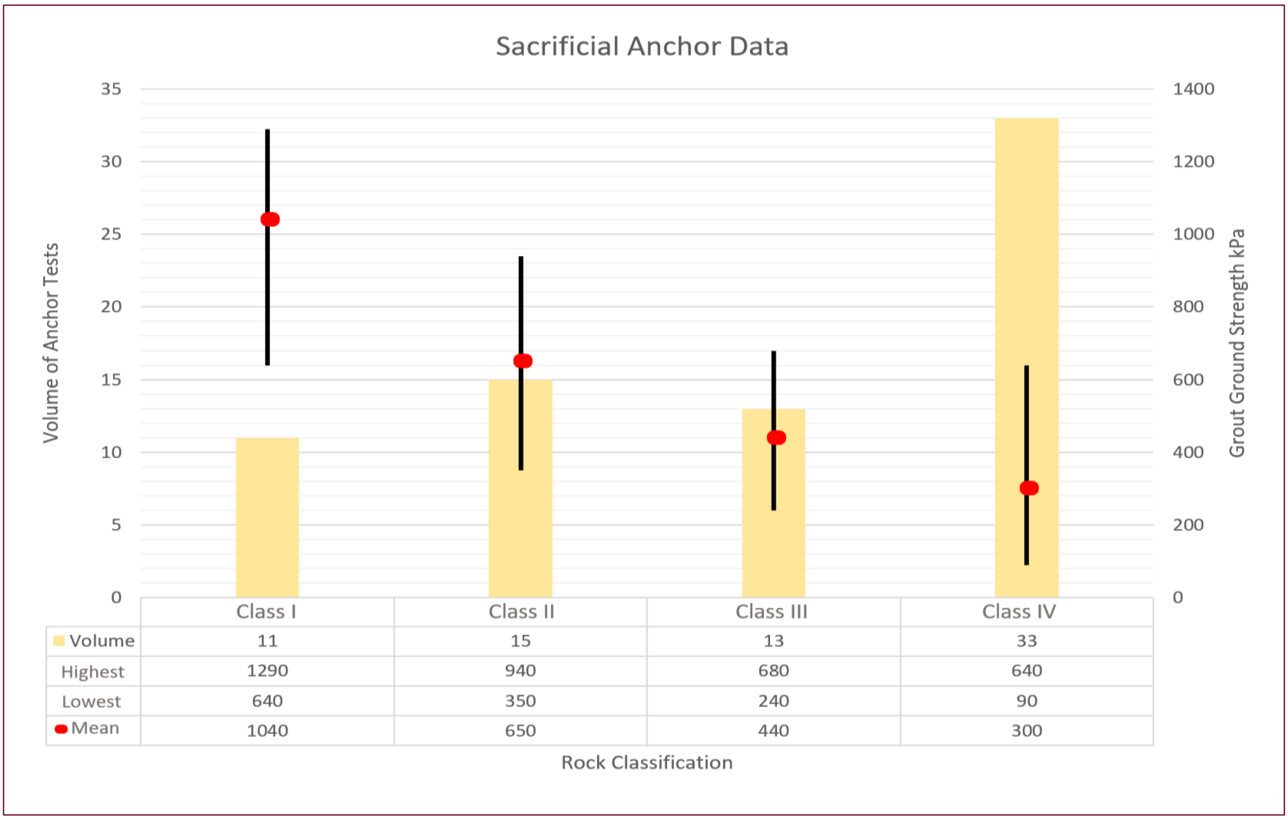


Figure 3: Grout to ground bond strengths using the NCTIR Rockmass Classification

As expected, the anchor testing results show a gradual increase in the grout to ground bond strength as the rock mass improves. However, the ranges of bond strengths within each classification are relatively large, with the highest and lowest results often overlapping with two and three classifications. The highest result in Class IV (640 kPa) is within the range in all classes, including being the lowest value of Class I. The wide range in each class is assumed to be a consequence of different weathering profiles below the surface. In some cases, the Class IV rock/colluvium will be a relatively shallow layer confined to the surface with much more competent (Class II to III) rock at a shallow depth providing higher bond strengths. Conversely, in some cases Class I rock observed at surface may have persistent and open defects that extend well beneath the surface resulting in a deeper weathering profile or more frequent kinematic controlled instabilities that may be reduce the overall bond strength.

4.2 Part 2: Predicting Values

The NCTIR Rock Mass Classification system is intended to provide an indication of the structure and surface quality of the geological units observed across the NCTIR sites. The majority of sites, especially south of Kaikōura, are dominated by Greywacke. New Zealand Greywackes are generally a combination of high intact rock strength (100 MPa or more) with close jointing and structures which are often tectonically disturbed. Due to the variability within Greywacke it can be challenging to accurately predict an appropriate grout to ground bond strength from surface observations. As the classification system is based on surface geology, the different classes can be approximately associated to the weathering profile, varying from unweathered (Class I), slightly weathered (Class II), moderately weathered (Class III), down to highly weathered or colluvium (Class IV).

In the original paper introducing the NCTIR Rock Mass Classification (Macfarlane and Justice, 2017), the four classes of rock were overlaid on the Geological Strength Index from Hoek (2002). This is shown along with the recorded grout to ground bond strengths within each classification category overlaid in Figure 4.

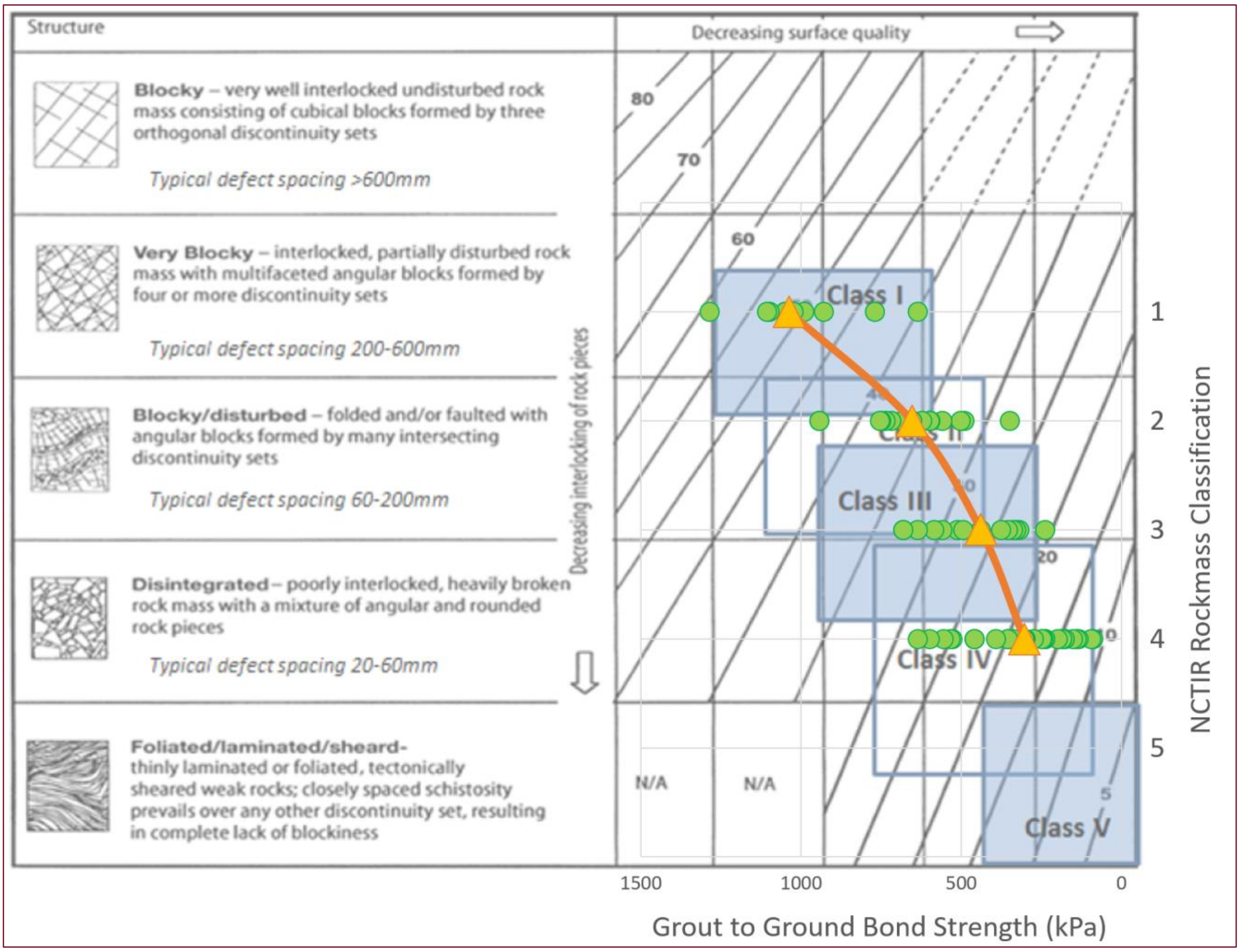


Figure 4: Predicted bond stress based on case history data compared to NCTIR rock mass classification (Macfarlane and Justice, 2017) and the Geological Strength Index (GSI) from Hoek et al. (2002).

The individual results, marked green on Figure 4, illustrate the wide range of bond strengths within each classification. There is a clear gradual increase in the average grout to ground bond strengths marked by the orange triangles and trend line. This suggests that the NCTIR Rock Mass Classification should be used more as a scale to enable a more accurate estimation of the grout to ground bond strength. Many rock types are likely to fit among the boundaries of each class, such as a Class I/II or Class II/III rock.

An appropriate use of the classification system and compiled dataset could be to initially identify the main rock class using the NCTIR Rock Mass classification system to provide a range of expected bond strengths. Initial estimates could be refined by a review of the structure and surface quality, to identify whether the particular rock is within a boundary of two classes to enable a more refined estimation of the bond strength.

4.3 Uncertainties

The figures presented in this paper indicate a rough, but clear trend. There is, however, noticeable scatter in the data. The most significant uncertainties are likely to arise from the following sources:

1. Testing conditions – Although Figure 2 suggests a standardised set-up for testing, the reality of this installation depends greatly on the location of these tests. The variety of set-ups can be seen in Table 1, with varying amounts and complexity in cribbing, often with a requirement for roped access.
2. Drill hole diameter – variations in the actual surface area of the grout column are likely to be significant, particularly in cohesionless colluvium and highly fractured rock where some degree of 'inter-fingering' in the void spaces is likely to occur.

3. Drilling / installation method – conventional drilling methods generally use gravity grouted anchors or pressure grouted systems. However, pressure grouting will vary by contractor and the actual pressure magnitudes can have a significant effect in some materials (FHWA, 1999).

To explore some of these uncertainties further analysis could be completed with the addition of the acceptance testing results. Due to the quantity of the acceptance testing data, it has not been compiled into a single dataset. Detailed assessment of the acceptance test results could provide additional valuable information on bond capacities.

5 CONCLUSIONS

This paper has presented the analysis of the sacrificial anchor testing results from the geological units found along the southern Kaikōura coast identified using the NCTIR Rock Mass Classification system. This classification system and the dataset presented provides a clear approach for estimating the expected grout to ground bond strength and with some ground truthing could be useful on other projects within similar geological settings.

Based on the upper and lower quartile results for each rock class, the authors recommend the following ranges for future design in similar rocks using the NCTIR rock mass classification system:

- Class I 740 – 1100 [kPa]
- Class II 590 – 800 [kPa]
- Class III 300 – 640 [kPa]
- Class IV 200 – 510 [kPa]

Between each classification will exist an intermediary class (i.e. I/II, II/III, and III/IV). These intermediary classes should be considered and based on the structure and surface quality observed on site. The use of a scaled classification and ability to refine rock types based on the structure and surface quality will improve the accuracy of the estimated grout to ground bond strengths.

6 ACKNOWLEDGEMENTS

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