Pull out resistance of soil nails in continuous auger drilled holes

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ABSTRACT

Continuous auger drilling for soil nail and ground anchor installation is common practice in many parts of the world. However, caution is required when using this drilling technique in Auckland, New Zealand due to the risk of soil smear adversely affecting the grout to ground bond strength. Rotary drilling with air flush is typically preferred to mitigate this issue. Accordingly, rotary air flush drilling was used to install many of the soil nails and ground anchors across the NZ Transport Agency's Waterview Connection project in Auckland. The project involves construction of a new 5km long three lane motorway including 2.5km long twin three lane tunnels up to 35m deep with associated retention and portal works in urban Auckland. The exception was at the northern end of the project where the risk of air flush debris ejection onto live traffic lanes and adjacent construction activities required the use and testing of augering techniques for soil nail and ground anchor installation. This paper reports the pull out resistance of soil nails and ground anchors installed in holes drilled using both unflushed continuous flight auger and flushed rotary drilling techniques. Particular focus is given to pull out testing of soil nails in continuous flight auger drilled holes and grooving of the augered hole to improve poor pull out performance due to soil smearing.

Keywords: soil nails, anchors, pull out resistance, auger, alluvium, grooved

1 INTRODUCTION

The pull out resistance of individual nails is a very important factor in the design of a soil nail system. A number of field pull out tests have been undertaken in Tauranga Group alluvium ('alluvium') and East Coast Bays Formation (ECBF) residual soil ('residual soil') as part of the Waterview Connection project in Auckland. These tests were undertaken to estimate and verify pull out capacity adopted for design of soil nail retaining walls. Test nails were drilled using both air flush rotary and continuous flight auger drilling techniques, and the distal ends of the nails were grouted for pull out testing. Surprisingly low pull out resistance was observed for nails in the auger drilled holes, and this has been attributed to soil smear during drilling. Grooving of the soil bore was tested and proven to be a successful mitigation measure. Comparison with pull out test results for continuous auger drilled ground anchors on the project is also discussed.

2 PROJECT DESCRIPTION

The Carrington Road retaining walls (RW601 and RW603) are being constructed at the northern end of the Waterview Connection Project. These walls are to enable widening of SH16 to accommodate additional slip lanes for the interchange to SH20 and the Waterview tunnels. The retaining walls include soil nail walls up to 8m high and 400m long. Soil nails comprise BluGeo Powerthread K60 glass-fibre reinforced plastic (GRP) solid bar with associated glass-fibre nail plates, nuts and stainless steel couplers. The GRP components simplify the design and construction of the nails, as the complex triple corrosion protection measures usually required for steel reinforcement are not needed. The soil nails are up to 15m long and are grouted into 150mm diameter holes on a triangular grid at 1.3m centres.

3 GEOLOGY AND GEOTECHNICAL DESIGN PARAMETERS

The site is generally underlain by Tauranga Group alluvium ('alluvium') and East Coast Bays Formation (ECBF) residual soil ('residual soil'). The alluvium generally comprises firm to stiff, silty clay and clayey silt. The residual ECBF soil is a stiff to very stiff clayey silt. Geotechnical design parameters were based on in situ testing, laboratory testing and back analysis of existing slope failures. The following parameters were adopted for the alluvium and residual soil:

Table 1: Geotechnical parameters for soil

Geological Unit	Unit Weight (kN/m^3)	Effective cohesion (kPa)	Effective friction angle (degrees)	Drained Young's Modulus, E' (MPa)
Tauranga Group Alluvium	18.5	5	29	15
Residual ECBF soil	18.5	5	30	20

4 PULL OUT RESISTANCE FOR DESIGN

The pull out resistance of individual nails is a very important factor in the design of a soil nail system (Heymann and Rohde 1992). Shear stresses are mobilised between the surface of a soil nail and the ground due to relative movement between a soil nail and the ground. Bond failure will occur when the limiting value of bond stress is reached and the nail will pull out of the ground (BS8006-2 2011).

A geotechnical ultimate grout to ground bond strength of 50kPa was adopted for the alluvium and residual soil. This strength was selected based on measured undrained soil strengths and destructive soil nail pull out tests undertaken prior to design (described further in Section 5). A factor of safety of 2 on the ultimate bond strength was adopted when determining the design bond strength. This was considered appropriate based on the available test information.

The design of the soil nail walls was generally undertaken in accordance with Ciria C637, the NZTA Bridge Manual (2nd Edition) and BS8006-2:2011. A limit equilibrium approach using SLOPE/W software was used to model the soil nail walls and calculate a factor of safety (FOS) for potential local and global slip mechanisms. The soil nail spacing and lengths were determined based on the SLOPE/W computation of pull out forces and anchorage lengths required to reinforce the ground to achieve minimum FOS criteria (static>1.5, temporary >1.2, seismic>1.1).

5 FIELD PULL OUT TESTS

Destructive soil nail pull out tests were undertaken prior to design, and again near the locations of the retaining walls before installation of production nails. Five preliminary pull out tests were carried out in alluvium and residual soil prior to design to determine an appropriate grout to ground pull out resistance for design of the retaining walls. The preliminary pull out tests typically comprised relatively short 3-5m long RB25 Reidbar nails installed in vertical, 150mm diameter holes. These tests were undertaken using conventional rotary drilling with air flush.

Following these initial tests, the constructor elected to use a continuous flight auger with no flush to drill holes for the soil nail retaining walls. This was due to the risk of conventional rotary, air flush drilling ejecting debris onto live traffic lanes. A total of 17 pull out tests were carried out on nails installed in auger drilled holes to confirm the pull out strength adopted for design. These test nails comprised either a 7m or 10m long RB32 bar with a 4m bond length. The nails were installed in a 150mm diameter hole at an angle of 20 degrees, which is consistent with the design inclination of the production nails. The pull out testing is summarised in Table 2.

Test equipment included a hand pump operated hydraulic jack bearing on the test reaction frame with two dial gauges monitoring nail displacement and deformation of the ground beneath the reaction frame. During the pull out tests, nails were subjected to a number of load cycles (up to 60 minutes long) until failure of the grout to ground bond occurred. The load-displacement behaviour of the nail was recorded during the tests and the pull out resistance of the nail (T_{ult}) was obtained by dividing the peak pull out force by the active surface area of the nail:

$$\tau_{ult} = \frac{P_{ult}}{\pi D L}$$

P_{ult} = peak pull out force (kN)
D = diameter of the grout column (m)

Table 2: Summary of pull out testing

Drilling method	Geological Unit	No. of tests	Number of failed tests	Timing of test
Rotary air flush	Alluvium	3	Nil	Prior to design
Rotary air flush	Residual ECBF soil	2	Nil	Prior to design
Smooth Auger	Alluvium	10	4	Prior to construction
Smooth Auger	Residual ECBF soil	1	Nil	Prior to construction
Grooved auger	Alluvium	5	Nil	Prior to construction
Grooved auger	Residual ECBF soil	1	Nil	Prior to construction

5.1 Pull out tests on nails in ungrooved auger holes

Four of the eleven pull out tests undertaken on the 'smooth' (ungrooved) auger holes failed to achieve the ultimate bond capacity assumed for design (50kPa). At failure the nails typically experienced large displacement. Figure 1 shows the load-displacement plot for one of the failed nails.

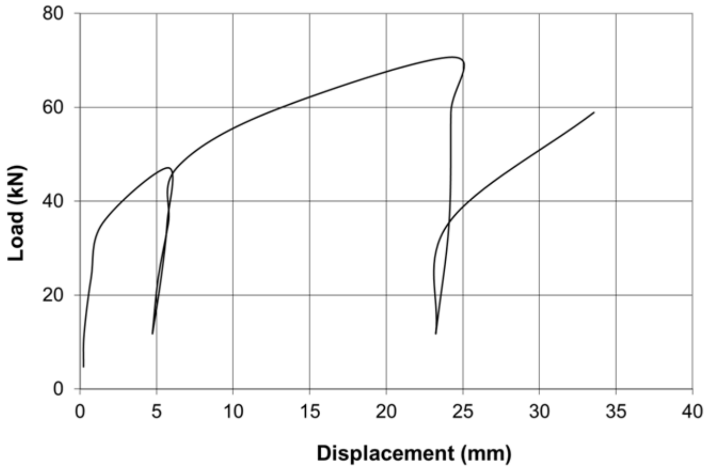

Figure 1. Load-displacement plot for a failed nail in a 'smooth' auger hole (Ch14690mm RW601)

5.2 Pull out tests on nails in grooved auger holes

Options to reduce the nail spacing or make the nails longer to achieve the required capacity were limited due to site boundary constraints. The constructor (Brian Perry Civil) developed a specialised tool comprising an adjustable 'permanent spike' which was welded to the drill head as shown in Figure 2. This tool creates a groove down the length of the hole which is around 15mm deep and 20mm wide (Figures 3 and 4). All six pull out tests on nails installed in the grooved auger holes achieved the required design grout to ground bond capacity. Figure 5 shows a typical load-displacement plot for one of the nails in a grooved auger hole.

Figure 2. Adjustable spike on the drill head

Figure 3. Grooved auger hole

Figure 4. Ribs on the exposed grout column

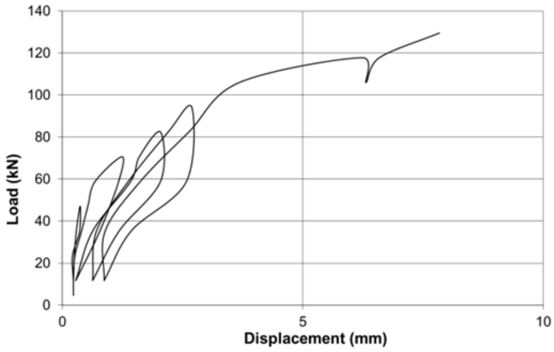

Figure 5. Load-displacement plot for a grooved auger hole (Ch7741m RW603)

6 SOIL NAIL PULL OUT RESISTANCE

The pull out resistance (τ_{ult}) obtained from each of the pull out tests in the alluvium and residual soil is shown on Figures 6 and 7 respectively.

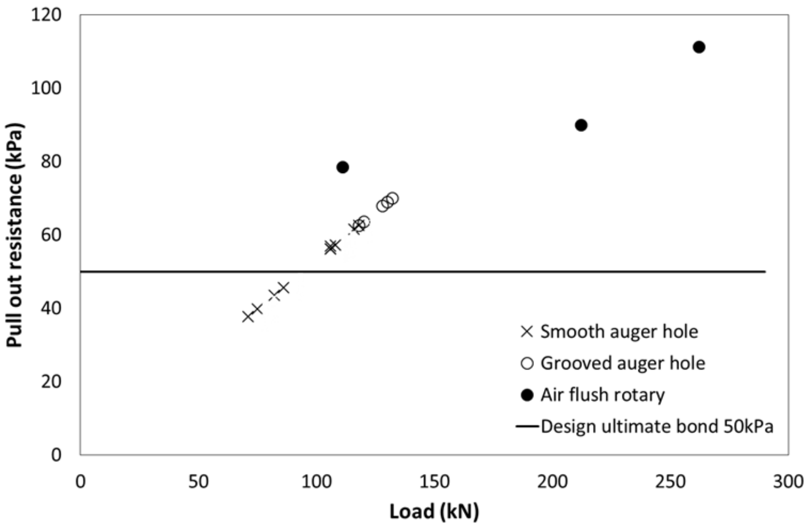

Figure 6. Pull out resistance in alluvium

The results show that the nails in alluvium which were drilled using the air flush rotary drilling technique achieved significantly higher values of pull out resistance than auger drilled holes (Figure 6). A reduction in the mean pull out resistance of 44% and 29% was observed for the 'smooth' (ungrooved) and grooved auger holes respectively.

Nails in the ungrooved auger holes had a variable pull out resistance ranging from 38kPa to 63kPa and a number of these nails failed to reach the 50kPa design requirement. Test nails installed in the grooved auger holes performed better than the nails in the ungrooved auger holes with all tests achieving the required 50kPa pull out resistance. A modest 7kPa increase in the maximum recorded pull out resistance values for the ungrooved and grooved auger holes was achieved (i.e. 63kPa maximum ungrooved vs 70kPa maximum grooved). An increase of 15kPa was achieved on the average value of pull out resistance for all ungrooved and grooved auger hole test results. This represents a 22% increase in the average pull out resistance. More importantly, nails in the grooved holes produced much more consistent pull out test results with a tight range of 63kPa to 70kPa, meaning that all values exceeded the 50kPa design requirement.

Figure 7 shows that the limited number (4No.) of pull out tests in residual soil which all resulted in similar and acceptable pull out resistance values.

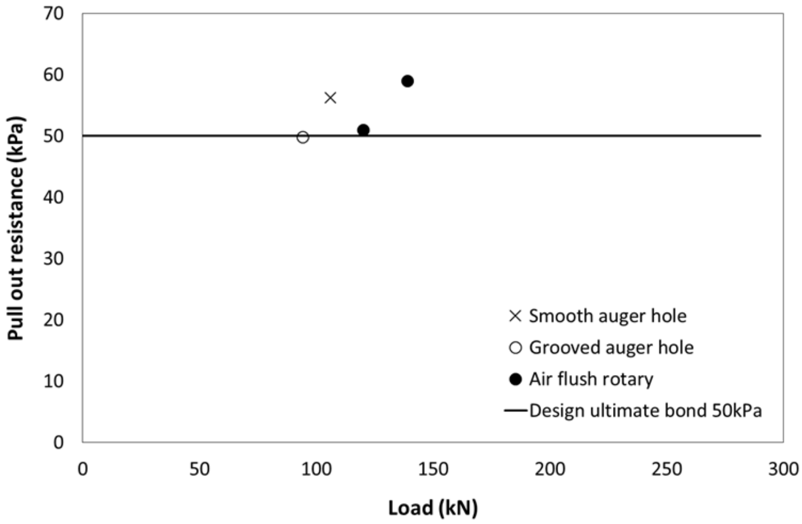

Figure 7. Pull out resistance in residual ECBF soil

6.1 Overburden

Overburden above the test nails varies with local topography and the length of the nail tested. Heymann and Rohde (1992), Schlosser (1982) and Cartier and Gigan (1982) report a constant pull out resistance for nails at different depths. However, Jewell (1990), Bridle (1990), Feijo and Erhlich (2003) and Pradhan et al. (2006) have suggested that normal stress between the soil and the nail at failure increases as the effective overburden pressure increases.

Luo et al. (2002) also argue that nail pull out resistance is dependent on depth and offer an explanation as to why experimental tests can appear to show that there is no relationship. They note that the dilation behaviour of the soil around the nail during the pull out process has a significant effect as it can govern the nail/grout to ground interface friction. Luo et al. note that if dilatancy is fully restrained by the surrounding soils then the normal pressure on the surface of the nail can be increased by up to 14 times, subsequently increasing the pull out resistance. It is reported that the apparent friction caused by the increase in normal stress due to soil dilation decreases with increasing normal confining pressure. The combination of the dilation effect and the diminishing effect with increasing overburden pressure counter each other and create an illusion that pull out resistance is independent of overburden depth (Lou et al. 2002).

The effect of overburden on pull out resistance in the alluvium has been considered. Figure 8 shows pull out resistance for nails in the grooved and ungrooved auger holes plotted against overburden pressure. Results generally show an increase in pull out resistance with increasing overburden for the ungrooved holes and no significant relationship for the grooved holes. It is considered that soil smear (discussed in Section 6.2) is likely to be having a significant and variable effect on pull out resistance, making it difficult to make a meaningful assessment of the influence of overburden pressure.

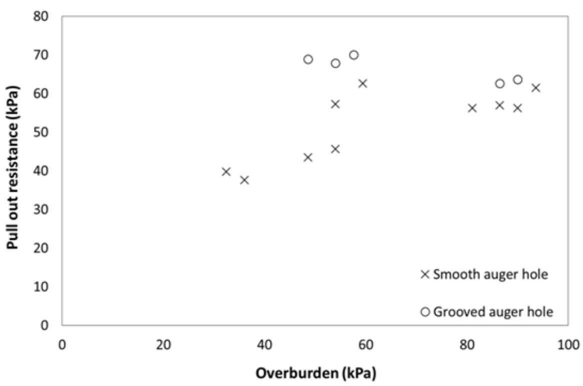

Figure 8. Pull out resistance relative to overburden pressure in alluvium

Figure 9. Soil smear on the pulled [ungrooved] grout column

6.2 Soil softening by smearing

It is considered that the low pull out resistance in the ungrooved auger holes in alluvium is likely to be the result of pull out failure occurring in softened soil smeared onto the side of the hole as soil cuttings are pushed back up the hole by the continuous auger. Two key observations support this conclusion. First, a layer of softened soil was observed on the grout column of one of the failed nails (Figure 9) which was pulled out of the ground (pulling the nail may have contributed to the observed soil smearing). Secondly, a number of nails encountered a thin, black, organic soil layer at depth. During drilling it was observed that the black soil from depth was smeared over the in situ orange coloured soil in the upper part of the hole (Figure 3).

It was also observed that the grooving tool cut through the black smear layer very effectively, exposing natural ground in the groove created (Figure 3). Variability in the pull out results for the ungrooved auger holes (38kPa to 63kPa) may reflect the variable nature of the alluvium, with some tests located in material more susceptible to strength loss when being reworked and smeared during drilling.

The limited number of pull out tests on nails installed in auger drilled holes in residual ECBF soil (2 No.) did not exhibit similar trends to those observed in the alluvium. In practice, it is expected that smear of these soils during continuous flight auger drilling has the potential to cause poor pull out performance.

7 AUGERED GROUND ANCHOR PULL OUT COMPARISON TO SOIL NAILS

Pull out testing of non-production multi-strand ground anchors was also undertaken on the Waterview Connection Project. Pull out test results have been reviewed for comparison with soil nail pull out test findings. The test anchors were grouted into unweathered, extremely to very weak interbedded sandstone and siltstone of the East Coast Bays Formation, and were undertaken to assess the ultimate strength and creep characteristics of the grout to rock bond for design.

Three test anchors were drilled at the Southern Approach Trench (SAT) for the road tunnels using percussion drilling with air and water flush and the pull out results used as the basis for design. Two further test anchors were later drilled at the northern end of the project at the Northern Approach Trench (NAT) using a continuous flight auger and no flushing as shown on Table 3. These anchors were tested to assess the viability of this drilling technique, as eliminating airborne flush debris would have been advantageous in the tight confines of the NAT.

Table 3: Summary of ground anchor pull out testing

Anchor	Drilling method	Pull out resistance τ_{ult} (kPa)	Creep deformation criteria
SAT1	Percussion (air/water flush)	1400	Pass
SAT2	As above	1000	Pass
SAT3	As above	1100	Pass
NAT1	Continuous flight auger (no flush)	1100	Fail
NAT2	As above	760	Fail

The multi-strand anchors were installed in vertical drill holes with a 4.2m long bond length. Anchor free lengths varied between 15m to 21m. Anchors in the percussion holes comprised 19 No. 15.2mm diameter strands in a 150mm diameter drill hole. Anchors in the augered holes comprised 15 No. 15.2mm diameter strands in a 200mm diameter drill hole.

Anchors were tested for a number of load increments and cycles. Creep deformation was also measured with the load held for predetermined time intervals at representative stages of the loading cycles. Permissible creep deformation of the test anchors at various load increments was calculated based on recommendations given in BS8081. The load-displacement plots for the two auger drilled anchors are shown in Figures 10 and 11.

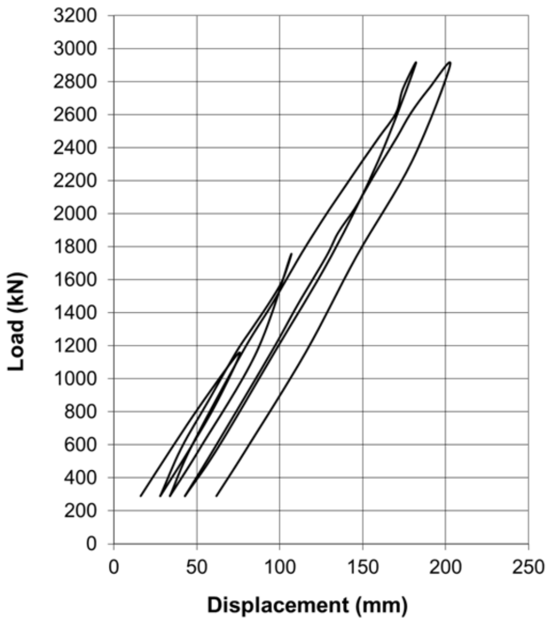

Figure 10. Load-displacement plot for NAT 1

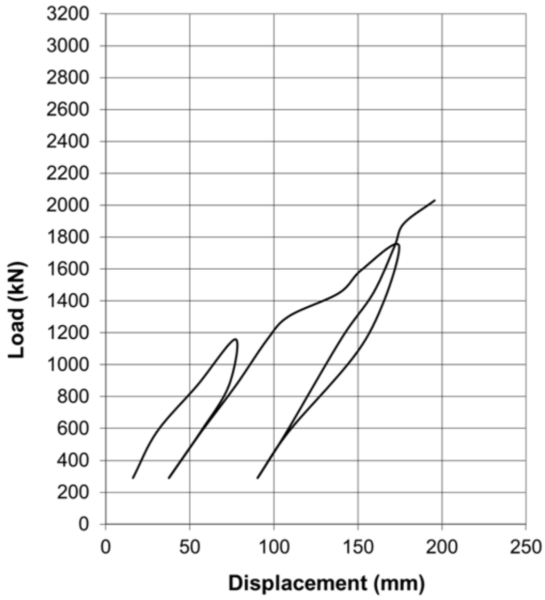

Figure 11. Load-displacement plot for NAT 2

All of the test anchors except one achieved a pull out resistance in the range of 1MPa to 1.5MPa, as shown in Table 3. Auger drilled anchor NAT2 failed at a pull out resistance of 760kPa, which was less than the 1MPa design requirement. Creep deformation in the three flushed, percussion drill holes was significantly less than permissible values and therefore acceptable. However, creep deformation in the two auger drilled holes greatly exceeded that permissible.

Figure 12 shows the calculated permissible creep values compared to the measured creep deformation for the two auger drilled anchors. The values shown in Figure 12 are for the third load cycle, in which creep deformations were measured over a five minute duration for different load increments representing 60% to 100% of the test load. The creep at 100% of the test load was measured over a longer 15 minute duration. Only two values are shown for Anchor NAT2 as failure occurred. It is noted that excessive creep deformation had already occurred at lower loads during the first two load cycles.

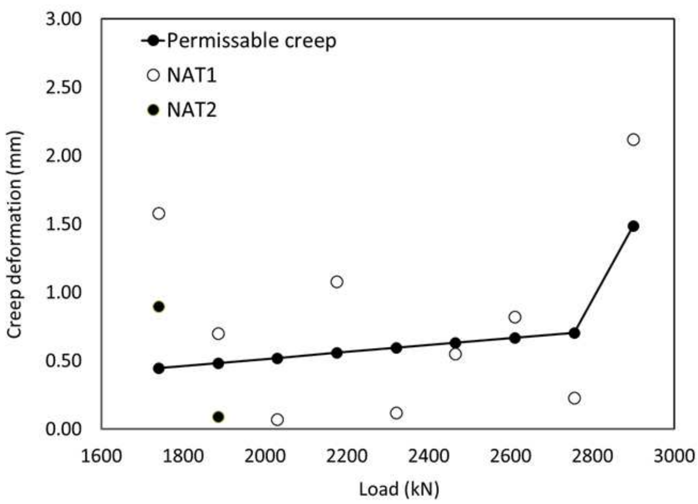

Figure 12. Creep deformation of the augered anchors (NAT1 and NAT2) for the third load cycle

It has been shown that soil nail pull out performance has been adversely affected by soil smearing. A similar pull out failure mechanism is a possible reason for the poorer performance of the continuous flight auger drilled ground anchors in ECBF rock. The presence of softened, remoulded drill cuttings smeared on the surface of the rock along the bond length of the anchor may be the cause of poor pull out performance and the excessive creep displacements measured. Grooving anchors in a similar manner to the soil nails was not considered as it was decided to revert to an air/water flush rotary drilling technique for ground anchor installation in the NAT and ensure that other construction activities in the trench remained well clear of the drilling works.

8 CONCLUSION

A number of pull out tests have been undertaken on soil nails grouted into alluvium and residual soil of the East Coast Bays Formation (ECBF) in Auckland. The soil nails were installed in holes drilled using both air flush rotary and unflushed continuous flight auger techniques. Nails installed in the auger drilled holes obtained a significantly lower pull out resistance than the nails in the flushed rotary drilled holes. Pull out failure in the auger drilled holes was occurring in weak, softened soil smeared onto the side of the hole as the auger pushes soil cuttings back up the hole. Ground anchors drilled into ECBF sandstone using similar continuous flight auger techniques were also found to have poor pull out performance and excessive creep deformation during testing and soil smear on the anchor bond is a possible cause. The effect of varying overburden pressure on soil nail pull out resistance has been considered with results shown on Figure 8. While trends were observed, the significant and variable weakening effect of soil smearing on pull out resistance makes meaningful assessment of the influence of overburden pressure difficult.

Pull out test results indicate that a reduction in pull out capacity of up to 30-40% can be expected if using unflushed, continuous flight auger drilling techniques in alluvium. A grooving tool was developed which cut through the softened soil smear on the side of the bore and resulted in a 20% increase in pull-out resistance and more consistent results. Accordingly, a cautious approach is advised when installing soil nails or ground anchors in Auckland using unflushed continuous flight auger drilling. An appropriately conservative pull out resistance should be assumed for design and grooving of the hole may be required to mitigate the adverse effect of soil smear.

9 ACKNOWLEDGEMENTS

The writers would like to acknowledge Brian Perry Civil for supplying the pull out test data and the Well-Connected Alliance (WCA) for permission to publish our findings.

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