Canadian Geotechnical Journal
Revue canadienne de géotechnique

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Journal:	<i>Canadian Geotechnical Journal</i>
Manuscript ID	cgj-2017-0048.R2
Manuscript Type:	Article
Date Submitted by the Author:	25-Jul-2017
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Keyword:	Soil nailing, pull-out test, soil reinforcement

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Laboratory Pullout Resistance of a New Screw Soil Nail in Residual Soil

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ABSTRACT: The ultimate shear strength at the interface between the soil nail and surrounding soil is of practical importance in the design and performance of a soil nail system. The most commonly adopted method of measuring this interface shear strength is by a soil nail pullout testing. This study introduces a novel soil nail system in the form of a screw nail and compares its performance with a conventional grouted soil nail. Both types of soil nails are tested in a controlled laboratory setting using residual soil in a large purpose made pullout box. The development of the screw nail and the laboratory testing procedures are briefly discussed first followed by presentation and discussion of the results on the interface shear behaviour measured from pullout tests. It is shown that the screw nail offers many advantages in terms of pullout load-displacement behaviour and the interface shear mechanism than that of the conventional grouted soil nail.

KEYWORDS: Soil nailing, screw nailing, pull-out test, retaining structures, soil reinforcement.

INTRODUCTION

The history of soil nailing probably began in the early 1960's with the first application of rock bolting support system for underground excavations with sprayed concrete. This method is referred to as the New Austrian Tunnelling Method (Kovari, 2003). This type of support system consists of the installation of passive (i.e., not prestressed as for ground anchors) steel reinforcement in the rock followed by the application of reinforced shotcrete. Because the method was cost-effective and the construction faster than other conventional support methods, an increase in the use of soil nailing took place in France and other areas in Europe as well as the US.

Although helical anchors were used by A. B. Chance (1977) as tiebacks, but helical soil nails are a relatively new alternative to grouted soil nailing with the first documented use for a 6.7 m high permanent soil nail wall project in 1996 (Bobbitt 1996). The first known report of its construction and instrumentation was in 2005 by Missouri Department of Transport (MnDOT), Deardorff (2010).

In its simplest form, helical tieback typically consists of square shaft lead and helical flights spaced evenly along the entire shaft. The helical soil nail transmits axial and torsional stresses to the surrounding soil via the shaft and helical plates.

In the conventional sense, the basic elements of a soil nail comprise reinforcing bar, grout, threaded nail head, nut with bearing plate and shotcreted facing. Moreover, helical soil nail just comprises of helix, shaft and shotcreted facing with some kind of mechanical head tie down.

Low cost and quick construction period are the main reasons for the increasing usage of soil nailing. Various construction methods that exist for placing nail in soil include drilling and grouting and that of firing using a compressed air gun.

A literature review reveals very limited studies conducted on the helical soil nail, in particular their behaviour and interaction is not yet fully understood. In this study, laboratory pullout tests were carried out on a model screw nail as well as grouted nail to determine the pullout behaviour of helical screw soil nail in compacted residual soil with a specific focus on the study and testing of the soil-nail interaction. Therefore, a large scale laboratory setup comprising a test box, loading frame and a pulling actuator was used to conduct the full pull out testing. The results of the tests performed are analysed and compared to other published works.

Various theoretical and empirical methods have been proposed (Schlosser, 1982; Cartier and Gigan, 1983; Jewell, 1990; Heymann et al., 1992) for the evaluation of pullout resistance of soil nail, which is considered an important design parameter that is often estimated and it is then verified by pullout test during construction. The peak pullout resistance is given by Milligan & Tei (1998):

$$\tau_{max} = \frac{P}{\pi DL} \quad 1$$

Where P=peak pullout force, D= soil nail diameter and L=length of soil nail.

The coefficient of friction f is given by the following equations:

$$f = \frac{\tau_{max}}{\sigma_n} \quad 2$$

Where,

$$\sigma_n = \frac{(1+k_0)}{2} \sigma_v \quad 3$$

Wang et al (2017) carried out an interesting study to investigate the effects of grouting pressure on the pullout resistance of soil nail by using an impermeable membrane in the bore cavity to prevent the migration of grouting paste into the surrounding soil. This migration of the cement paste has been shown in numerous studies to have a deleterious effect by softening of the surrounding soil. In the study by Wang et al (2017) it was shown that by using the membrane preventing the grout movement into the soil, better pull out resistance results were obtained due to the densification of the surrounding soil.

Cheng et al (2016) used carbon fibre-reinforced polymer and glass fibre-reinforced polymer in various forms and installation methods to investigate the bond strength. The study supported the suitability of the materials under the investigation and their performance to be acceptable in the testing conditions.

Hong et al (2013) developed a grouting packer system to test soil nails in the field using various grouting pressures in different soils. It was found that the apparent friction coefficient increased linearly with increasing grouting pressure. Further, more consistent with the current study, it was found that the failure surface of the soil nail shifted into the surrounding soil as a result of the grouting pressures.

Recently helical soil nail have been used to further improve the construction efficiency and costs of conventional soil nailing. It was envisaged that the helical soil nailing offers many advantages over the conventional soil nailing as it does not require any boring and grouting, and therefore, it can offer a more economical solution than the conventional method.

It is understood that for the grouted nail the bond strength is developed at interfaces and for the helical it is assumed to develop at the helices. As yet, there have been limited studies undertaken to understand the fundamentals of the mechanism involved in the analysis of helical soil nail. To this end, an experimental study of the fundamental behaviour of a helical screw soil nail has been conducted using a large shear box. A brief description of the screw soil nail and the apparatus as well as results of the tests conducted to date are described in the following sections. At the end a section is dedicated to discussing some of the limitations of the screw nail.

THE SCREW NAIL

It is well known that earth retention incorporating soil nail construction is unfavourable in soil conditions consisting of silt, sand, gravels, cobbles and boulders. The difficulty is that it is very difficult if not impossible to install a grouted soil nail in these types of soils. The main design philosophy behind the development of the screw soil nail was to allow for easy and quick installation particularly in the granular soil types and minimise ground disturbance in the soil as the nail installation proceeds.

It was therefore important that the helix geometry provided the downward force or thrust that pushed the nail into the ground with minimum soil disturbance. The tip of the helix was designed so that it increased the soil density and radial soil stresses around the helices. If the helices are not designed well it will tend to remould and remove the soil as it penetrates the soil resulting reduced soil stresses. It was with this understanding that the head was designed in the tapered form to allow for the soil to cut out rather than remould and displace. The main feature of the tapered head is that it consists of three helices with each helix having different plate thicknesses.

It is therefore envisaged that the screw nail would perform better than either of the soil nail systems due to minimal soil disturbances and the minimal loss of shear resistance due to soil remoulding. Other advantages the screw nail offers is that the penetration and torque are optimised for this type of system and it will also eliminate 'bridging' as is normally the case with the grouted soil nails due to stress relief because of pre-drilling work.

Other advantages of the screw soil nail are:

- Better nail-ground interaction because of no drilling involved, hence resulting in increased pull-out capacity,
- Suitable for all ground conditions including sands and gravels,
- Easy installation with no spoils or grouting,
- Screw soil nail can be effectively used fill slopes and earth retaining structures to eliminate pore water pressure build up,
- Failure mechanism is very different than the conventional soil nails,
- Well suited to specialist applications such as rehabilitation of distressed retaining structures,
- The limitations of the screw nail are discussed at the end of this paper,

The important feature is its ability to generate slip pull-out resistance that is different from other inclusions such as steel bars. However, very little is known about this mechanism that generates pull-out resistance. In order to identify this mechanism, a specially designed soil nail in the form of screw was fabricated and tested in large size box using residual soil. It is thought that this novel design will offer very efficient, cost effective and environmentally friendly alternative solution to the existing soil nail practice. Figures 1 and 2 shows the screw soil nail features and the laboratory test setup adopted, respectively.

A large size box was fabricated to allow the pullout testing of the prototype screw nail and to allow for detailed instrumentation. The box illustrated in Figure 2 show the overall arrangement of the box. The inside nominal dimensions of the box are $1\text{m} \times 1\text{m} \times 1.5\text{m}$. Four 50mm diameter bolts were welded to the bottom of the box and fastened to a large test frame assembly on the floor. A 150mm diameter hole was cut in the front plate of the box for the insertion of the screw nail. The middle four steel members were extended and connected on the top to help with the application of the vertical pressure by a pneumatic jack connected to a fully automated hydraulic pump as described in the following section. A separate stiffened plate was made to fit just inside the box to exert the stress onto the soil in the box. The box was mounted on a large custom test frame so that the nail is in level with the crosshead fitting.

TESTING APPARATUS

References were made to the works of various researchers (CF Lee etc. 2001; CY Hong etc. 2013; and JK Liu 2014) who carried out the experimental study on the pullout resistance of soil nails in the field and in the laboratory. In this study, a specialised testing apparatus using a high precision double-acting MTS actuator rig fitted with high capacity force transducer and LVDT was set up for pulling the screw nail. The actuator pull-out force to the screw soil nail and the LVDT measurements of the displacement were recorded by a DT80 data logger system and shown in real time. For the application of the vertical pressure, a 20 tonne Enerpac series single acting hydraulic jack connected to an automated hydraulic pump system was used. Four load cells were used inside the box to measure the stresses in the soil during pullout tests. An additional load cell and a laser LVDT were used to measure the surcharge on the top plate and its displacement during pullout testing. Two strain gauges were installed on the shaft between the two helices of the screw directly opposite each other.

TESTING PROCEDURES

The box was firmly fixed on the test frame adjacent to the hydraulic actuator. Residual silurian soil was moisture conditioned in a large enclosed mixer and let for moisture to stabilise before compacting. The

compaction was carried out in 50mm lifts at 95% maximum dry density at around 3% dry of the optimum moisture content or 12% moisture content. The main reason for compacting the soil on the dry side of the optimum moisture content was to reduce the effect of pore water pressure as much as practical. The densification process of the soil was carefully carried out by weighing the soil and compacting to horizontal line markings inside the box. Furthermore, consistency was measured with a shear vane and pocket penetrometer at six random locations on each compacted soil layer. During the compaction, two load cells were placed in the vertical position near the bottom in the centre of the box and two additional load cells were placed in the horizontal position in the middle of the box along the wall. Fine sand was placed around the load cells to encapsulate them and to prevent them from any damage during the compaction process. An additional load cell was placed between the top plate and the jack accurately to measure and control the surcharge loading.

A laser LVDT transducer was placed on top of the box to measure the top plate displacements during the application of stress and testing. Two strain gauges were installed in the middle of the on the shaft of the screw soil nail.

At the completion of the compaction process, pressure readings were taken to establish the initial state of the pressure in the box without the application of the surcharge pressures. Also, following the application of the first surcharge, the box was left 24h so that the stresses and strains reach equilibrium.

Relatively low surcharge pressures were chosen due to concerns about the hydraulic jack overheating because of the requirement that the pressures on the top plate needed to be maintained for a long duration. Therefore manageable surcharge pressures of about 5kPa, 10kPa and 25kPa nominal were applied by the automatic hydraulic jack system for about 24 hours for each stage of the pullout tests.

The screw nail was inserted into the box manually by a pair of stilsons. The penetration of the nail required minimal effort and the travel distance was same as the pitch distance per rotation. However, the installation of the grouted nail was rather messy and time consuming as grout was injected with the aid of a tremie pipe into the box hole created by the screw nail and it was allowed to set for about one week. The

grout mix for the nail consisted of 10mm nominal gravel, river sand and a water and cement ratio of approximately 0.45. A 22mm reinforcement bar was inserted in the centre of the grout and was connected to the actuator rig for pulling tests.

Both the screw nail and the grouted nail were pulled in multistage at slowly at a rate of 1mm/min. The rate was set at 1mm/min for all the nail pullout test and 0.5mm/min for the direct shear tests.

All the instrumentations including the actuator rig were connected to a DT80 data logger and data were recorded and displayed in real-time.

RESULTS OF LABORATORY TESTS

A series of laboratory tests were carried out in order to establish the properties of pulverised residual soil material used for this research. The tests included moisture content, standard compaction, Atterberge limit and direct shear tests as well as particle size distribution. The tests were carried out according to the relevant sections of the Australian standards AS1289. A summary of the test result is given in Table 1 and the plot of particle size distribution is depicted in Figure 3.

The residual soil used in the study contained about 28% fines and based on this grading test the soil may be described as low plasticity silty clay with some coarse-sized sand particles.

Standard direct shear tests (DST) were carried out to determine the shear strength parameters of the residual soil. Shearing tests were carried out at normal pressures ranging from 25 to 100kPa. The result of the normalised DST is shown in Figure 4 and the plot of the peak shear stress against the normal pressure applied is shown in Figure 5.

The soil friction angle estimated from the DST was 33.6° . The material did not have any residual strength as indicated by the shear vane and pocket penetrometer measurements during the compaction of the soil layer given in Table 2.

RESULTS OF PULLOUT TESTS

Plots of the pullout force against the nail displacement are shown Figures 6 and 7 for screw and grout nails respectively. The measured and theoretical surcharge pressures together with the peak pullout loads as well as the associated pullout displacements for both types of soil nails are shown in Table 3. A comparison of the calculated peak shear resistance, peak pullout resistance and the apparent coefficient of friction are given in Figures 8 and 9, respectively.

Several authors (Schlosser 1982; Heymann et al. 1992; Junaideen 2001; and Pradhan 2006) carried pullout tests on grouted nails embedded in various soils. They concluded that the pullout resistance increases with overburden pressures and that the interface parameters obtained from the pullout tests are close to the soil strength parameters determined by the direct shear box tests. They attributed the relationship between the pullout resistance and overburden pressure to dilatancy characteristic of some soils, but for loose and clay soils the dilatancy effect could be considered negligible. It should be noted that an important consequence of the dilation property of soil is that they show peak strength followed by a reduction in strength as the critical state approaches. In the case of the residual soil, this residual or reduction in strength was not observed. A further discussion on the results of the loading cell stress measurements given in later section also shows this effect.

The distinguishable features of the load-displacement curve are recoverable displacement of 3-4mm and the gradual increase in the peak force. The peak load occurred at the approximate displacement of 49mm for all the three overburden pressures. The residual value is not seen up to the maximum pullout displacement.

However, for the grout nail the curve has a slight curvature in the initial linear part of the load-displacement curve. The best linear curve fitting for this linear part give a displacement of approximately 5-9 mm before reaching the peak force fairly shortly. The peak load is maintained by the grout nail up to a displacement of about 35mm before dropping slightly at this displacement.

Despite all this, the most interesting and unexpected results of the two nails are that for the grout nail, unlike the screw nail, the peak pullout loads were independent of the normal surcharge pressures and that

the behaviour is similar to an undrained condition. That is the maximum interface shear stress mobilised varied little (27.6kN to 29.6kN) and hence the reason for the flat curve or the friction angle in Figure 8. Furthermore, the mobilised peak shear resistance for the screw nail was dependent on the overburden stress and the cohesion and friction angle were 36.2kPa and 41.1° (Fig. 10), respectively. Hence, from the comparison of the cohesion and friction angle results for the two nails indicate that the screw nails performance is better.

The narrow margin of the peak pullout figures for the three surcharge pressures for the grouted nail may be attributed to the development of the shear zone. The reasons for this effect could be related to the fact that the slip plane is at or close to the soil-nail interface. Hence, the same maximum shear force is mobilised because the shear zone remain the same thickness and that the shearing does not extend beyond the soil nail interface. But, rather the pull out capacity of the nail reaches a limiting value.

Further, the peak pullout capacity is dissimilar for the screw nail in that the pullout capacity seems to be dependent on the surcharge pressure. This is very likely to be due to the screw helix-soil interaction and the development of the shear zone. For the purpose of illustration, Figure 8 shows the general shape of the grout nail after it was withdrawn from the box. The general shape is similar to that of the screw nail. Except, upon closer examination, it shows the diameter of the nail is larger than the screw nail and it seems that the screw nail expanded radially during the pullout test. A reasonable conclusion one can draw is that this radial expansion is effectively the zone of plastic deformation where the soil is completely remoulded. Of course, the area extending beyond this plastic zone lays the area elastic deformation.

In addition, comparison of the pullout performance for the screw nail when compared to grout nail show that the pullout capacity of the screw nail is higher. The screw nail enhances the soil around the tip helix and therefore the actual shear zones shift deeper into the surrounding soil resulting in better soil-nail interaction and hence the diameter resulting in better pullout-displacement response.

Apparent coefficient of friction is a useful parameter for correlating between pullout resistance and overburden soil pressure. A plot of the apparent coefficient of friction f calculated from pullout tests is

shown in Figure 9. The analysis of the apparent coefficient of friction, the results indicate that the value of the friction f is not constant but rather decrease with the overburden pressure and theoretically it should approach $\tan(\phi)$ as surcharge pressure increases. In the design of soil nail, the value of the soil-nail friction that controls the factor of safety of nail in slippage mechanism compare better. Therefore, from an efficiency point of view, the high adherence of the screw nail is better to use particularly in areas susceptible to earthquake excitation or where large displacements may occur.

Fig. 10 presents the effects of normal stress on the pullout shear strength. The result for laboratory test appears to follow the Mohr-Coulomb failure criterion. The apparent adhesion and friction angle were calculated to be 36kPa and 41° for the screw nail and for the grout nail they are 42kPa for adhesion and a low value of 7° for the friction angle.

The comparison of the parameters given in Figure 10 to that of the direct shear test results (Fig. 5) indicate that the results of the pullout resistance higher than the shear box test result. This could be due to the differences in the development of the shear and slippage zone in the soil and around the nail. For shear plane is planar for the shear box test and that for the screw nail the shear planes develop some distance away from the interface. The extent of which may be correlated in the following section on the results of the loadcells.

FAILURE MECHANISM

Extensive theoretical and experimental research works have been carried out on buried helical anchor by numerous authors to investigate their failure mechanisms in various soil types and anchor geometries. Laboratory tests to investigate the failure mechanism of the helical anchors have been widely reported by Mitsch and Clemence (1985), Mooney et al (1985), Ghaly et al (1991) and Tokhi et al (2016). The experimental observations of the failure modes of the anchor reported by these authors, despite some similarities, are somewhat different and yet it is indicated that there is no unanimity of views concerning

the mechanism governing the pullout capacity of anchors nor it is clear from the literature that research outcomes of the anchors can be applied to the soil nails.

Some of the fundamental differences between the two mainly are: (1) The modelling of anchors is done by the limit equilibrium method, whereas for the soil nails it is more accurately modelled by the kinematic limit equilibrium approach (Juran et al., 1990); (2) anchors may be prestressed during installation, but the soil nails are not prestressed; (3) foundation helical anchors are routinely installed on average torque and soil nails are installed based on the design length; (4) anchors are designed primarily for tensile loads with the compression and moment forces being insignificant, however, for the soils nails both axial and moment forces are significant (Juran et al. 1990); (5) the three methods for predicting the pullout capacity for the anchors are 'cylindrical shear', 'individual plate bearing' and empirical 'installation torque'; (6) soil nails are designed on the average allowable shear resistance; (7) the design analysis procedures take into account the shearing, tension and bending resistances for the soil nail and for anchors it is the tension and compression forces; and (8) most importantly, the confining soil stresses in the vertical and horizontal directions are dissimilar for the two types of inclusions, hence the failure mechanism is developed differently for the two systems and controlled by different parameters.

Although the failure mechanism of the nail was not investigated in the residual soil, but the results of finite element analysis that has been published elsewhere shows that the failure mechanism is similar to that reported by Mooney et al (1985) and shown in FIG. 11. Also the failure mechanism may be inferred in the residual soil by the shape and enlargement of the cast grout nail shown in FIG.8.

SOIL STRESSES

Soil stresses were measured with four load cells placed at the vertical (Loadcells 1 & 2) and horizontal (Loadcells 3 & 4) positions. The vertical load cells were positioned at 100mm above the bottom of the box and the horizontal cell were placed at about 400mm from the bottom of the box in line with the shaft of the screw nail. All four loadcells were placed around the two helices. The results of the stresses by the loadcells measured just prior to and during pullout test are given in Figures 12 and 13 for the screw and

grout nails, respectively. For convenience, all the results were plotted on the same axis and shifted to the right.

The vertical and horizontal stress changes measured by the transducers installed show to some degree the change in the normal stress at the soil-nail interface.

All the loadcells in Figure 12 are initially in compression and move in parallel except the loadcell 4, which is in tension only for the 10kPa and 25kPa surcharge pressures. The reason for this is that at the start of the first stage of the pullout test, the loadcell is approximately perpendicular to the tip helix and it is in compression. As the testing stage progresses, the loadcell move to the rear of the tip helix and it becomes in tension as the screw nail is pulled out. This result indicates that the tapered tip helix also contribute to the total pullout resistance of the soil nail.

Loadcells 1 and 2, which are located below the screw nail register similar values and the stress increases are nearly identical for the first two stages of the pullout tests. The minimum stress change registered by the loadcells during the tests was about 10kPa nominal and the maximum of about 30kPa. These stress changes measures by the loadcells indicate that both helices create compression zone well beyond the soil-nail interface and the magnitude of the stress change is an indicator of the efficiency of the interaction mechanism at transmitting shear stresses.

A very interesting feature of the stress measurements by the loadcells is that at certain nail displacements there is a sudden change in stress measurements during the application of pullout force. As indicated in the figure, this feature is only noticed for the 10 and 25kPa surcharge pressures. For the 10kPa surcharge, the first increase in the compression is at the displacement of 15.3mm and the changes in stress are 1.2kPa increase in compression (loadcells 1 to 3), and 3.3kPa reduction in tension (loadcell 4). The second increase is at a displacement of 38mm with the increase in stress are about 1.26kPa increase in compression (loadcells 1 to 3), and 2.6kPa reduction in tension (loadcell 4). Also, for the 25kPa surcharge the stress change is only noted at the displacement of 31.5mm. A summary of the parameters correlating to these features is given in Table 3.

Fig. 13 shows the plots of the stress measured by the loadcells for the grout nail. A comparison of the result with the screw nail indicates that the stress changes during the pullout test are relatively lower and the lines are comparatively flatter. Further, quite opposite to the screw nail, the sudden change in the stress values is only noted for the 25kPa surcharge pressure. Curiously the magnitude of this stress change is reversed. In other words, at the instant of the stress change, the loadcells that are in compression expand due to tension force and lose some of compression. Rather, the reverse occurred for the screw nail where the loadcells that are in compression, increased even more at the location of the sudden stress change.

Table 4 below gives the result of all the measured parameters coinciding with the sudden changes in the stress measurements during the pullout tests. For the pullout load and displacement measurements, the instruments did not register any sudden change and the readings were continuous, except for the highest 25kPa surcharge pressures, where they registered a small increase in the pullout load for the screw nail and a decrease in the pullout load for the grout nail. Clearly, this sudden reduction in the force for the grout nail is followed by a sudden increase in the pullout displacement. This observation is very interesting indeed. It is a result associated with deeper inner failure mechanisms of the two nailing system and is an area that requires deeper investigation and analysis.

The average plate pressure change was measured about 0.1kPa reduction for the screw nail and 0.1kPa increases for the grout nail.

Two strain gauges measurements show a small decrease in the shaft strain for the 10kPa surcharge pressure. For the higher 25kPa pressures, the value is somewhat less. Also, the actual readings of the strain figures indicate that the bending stress increases slightly as the surcharge pressures and the pullout load is increased.

CONCLUSION

A series of laboratory pullout tests of screw soil nail in silurian residual soils were performed. A suite of laboratory tests was carried out to characterise the soil and the summary of results was presented. The results of the pullout capacity, shear resistance and frictions coefficients were calculated and comparisons of the results for the screw and grout nail were presented. Further, results of the instrumentation the screw soil nail embedded in loose sand were carried out and the results were discussed.

The following observations and conclusions can be made on the basis of the work presented herein:

1. The pullout load-displacement curves for the screw nail are dependent on the surcharge pressure and for the grout nail, it independent of the surcharge pressures applied. Due to the characteristics of the residual clay soil, no sharp reduction and residual value are observed.
2. For small pullout displacements, the screw nail exhibits almost perfect linear force-displacement relationship indicating the displacement is recoverable and no plastic deformation has occurred. The pullout resistance at large displacements exceeds the so called peak value and therefore from an efficiency point of view, the high adherence of the screw nail is better to use in areas susceptible to earthquake excitation or where large displacement may occur.
3. The peak pullout shear resistance increases are linear with the increase of normal stress and follow the Mohr-Coulomb failure criterion for the screw nail. However, for the grouted nail the peak pullout resistance is uniform and exhibits a drained condition.
4. The results show that the peak pullout forces are mobilised at about 49 mm nominal for the screw nail. In the field condition, screw nail can also be expected to mobilise similar pullout capacity in similar ground movement.
5. The results of the loadcell transducer used around the screw nail show that the confining stress acting on the nail increases radially as the nail is pulled out. Consequently, for the screw nail the failure surface shifts deeper into the surrounding soil resulting in large slip diameter. Marginal stress increases are noted

for the grout nail, indicating the shear slip is at or near the soil-nail interface. The tapered tip helix also seems to contribute to the total pullout capacity of the nail.

6. Comparison of the pullout performance for the screw nail when compared to the conventional grout nail show that the screw nail performs better in terms of pullout capacity. The screw nail minimises the remoulding of the soil around the helices and therefore results in better soil-nail interface interaction mechanism.

7. Based on measured results of the apparent coefficient of friction measured in the pullout tests indicate that the pullout test result for the screw nail is better and that the pullout test is an appropriate method of obtaining design values of interface friction.

8. The apparent cohesion observed in laboratory is markedly higher than that derived for grout nail. The value of the cohesion and friction angle controls the factor of safety with respect to the failure mechanism by slippage.

9. The study has shown that the screw nail results in significant performance in pullout capacity over the conventional grouted soil nails. The potential for economical use of the nail would appear particularly great for areas where access is limited, rehabilitation of existing structures such as retaining walls and areas where soil drainage capability of the soil is required for the enhanced performance.

LIMITATIONS

Despite the aforementioned advantages of the screw nail, the major limitation of the screw nail is believed to be in soils containing large boulders. In these soils, the self-drilling advantage of the nail may be severely hampered. It should also be noted that length of the screw nail could be a limitation in practice, however this limitation can be resolved by using a specifically designed connection system to extend the installation length at added costs.

The failure mechanism is a very complex phenomenon and is dependent on many factors such as the soil density and type, helix diameter and spacing, plate thickness, shaft diameter among several others. To

investigate all and every aspect of these factors involved a huge amount of work needs to be done before clear and consistent results can be found. In this regard, the work presented here is rather limited based on the small number of tests. Nevertheless, in view of the current literature on screw soil nails, this work is believed to provide some basic groundwork for future work to continue in this area.

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Figure Captions

FIG. 1: 3D CAD model of screw nail.

FIG. 2: Details and setup of the laboratory test.

FIG. 3: Particle size distribution curve.

FIG. 4: DST test results on residual soil.

FIG. 5: Direct shear box test result.

FIG. 6: Pullout load-displacement curves for screw nail.

FIG. 7: Pullout load-displacement curves for grout nail.

FIG. 8: Exposed surface of grout nail.

FIG. 9: Comparison of peak pullout resistance and apparent friction coefficient with overburden pressure.

FIG. 10: Comparison of peak shear resistance for grouted and screw nails.

FIG. 11: Assumed failure mechanism for helical foundation anchor in (a) clay soil and (b) silt (modified from Mooney et al. 1985)

FIG. 12: Comparison of loadcells results for screw nail.

FIG. 13: Comparison of loadcells results for grout nail.

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TABLE 1: *Results of laboratory soil tests.*

Laboratory Tests		Results
Moisture Content	FMC* (%)	11.0
	OMC (%)	15.0
Compactive effort	95 % of MDD at 12 % MC.	
Maximum wet & dry densities	ρ_w (t/m ³)	2.00
	ρ_d (t/m ³)	1.74
Grading	Fines (%)	28
Atterberge Limit	LL (%)	31.0
	PL (%)	16.0
	PI (%)	15.0
	LS (%)	6.3
Direct Shear	ϕ_{ds} (°)	33.6

*FMC= Field Moisture Content, MC= Moisture Content after testing

TABLE 2: *Shear Vane and Pocket Penetrometer tests.*

Test	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
Vane (kPa)	62(0)	54(0)	56(0)	54(0)	52(0)	66(0)	64(0)	53(0)	55(0)
PP (kPa)	320	320	293	287	310	420	290	375	335

Number in parenthesis is residual strength.

TABLE 3: *Summary of pullout test results.*

	Grouted Nail			Screw Nail		
Theoretical Pressure (kPa)	5	10	25	5	10	25
Measured Pressure (kPa)	7.0	10.7	24.0	5.0	14.0	28.0
Peak Load (kN)	29.6	27.6	28.4	13.7	16.1	19.4
Displacement (mm)	34.2	28.1	47.6	49.2	49.2	49.9
Length (m)	1.29	1.24	1.19	0.60	0.60	0.60
$\tau_{\max}$ (kPa)	45.1	42.0	43.3	48.5	56.9	68.6
σ_z (kPa)	14.3	23.3	37.3	16.3	20.0	33.3
f (-)	4.03	3.01	1.83	4.94	3.50	2.60

TABLE 4: *Results of all parameters at the location of the sudden loadcell pressure change.*

	10kPa Surcharge (screw nail)		10kPa Surcharge (screw nail)		25kPa Surcharge (screw nail)		25kPa Surcharge (grout nail)	
	value	change	value	change	value	change	value	change
Pullout Load (kN)	16.7	0	18.9	0	15.7	0.046	27.8	-0.035
Pullout Displacement (mm)	15.3	0	38	0	31.5	0	26.4	0.049
Plate Pressure (kPa)	14.0	-0.085	14.2	-0.088	28.8	-0.12	23.9	0.1
Plate Settlement (mm)	27.1	0.053	27.1	0.029	28.9	0.054	29.1	-0.035
Strain Gauge 1 ($\mu\epsilon$)	70	-4.9	122	-5.1	99	-2	-	-
Strain Gauge 2 ($\mu\epsilon$)	96	-4.9	80	-5.0	162	-2	-	-
Loadcell 1 (kPa)	-48.5	-1.2	-55.5	-1.26	-59.5	-1.4	-56.5	+1.6
Loadcell 2 (kPa)	-49.1	-1.4	-58.7	-1.2	-70.5	-1.4	-69.8	+1.2
Loadcell 3 (kPa)	-28.7	-1.2	-40.6	-1.24	-47.9	-1.7	-99.6	+1.4
Loadcell 4 (kPa)	-1.8	-3.3	6.4	-2.6	13.6	-3.0	9.3	+3.1

For loadcells: -ve = compression; +ve = tension; () = indicate changes, -ve (compression), +ve (tension), /xx.xx=actual reading. All others: +ve = increase and -ve = decrease in value.