Pullout resistance of soil nails in unsaturated residual soils

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ABSTRACT

Soil nailing is a widely used slope stabilization technique using passive elements - soil nails (reinforcement bar within a grouted body). When the soil mass in a slope attempts to move down, the tensile force mobilized in the nail will increase the shear resistance by increasing the normal stress along the potential failure surface. Thus increasing the Factor of safety. The contribution of matric suction in pull-out capacity of soil nails is often neglected in conventional design formulae to make it conservative.

This paper investigates the influence of matric suction and overburden pressure on pull-out resistance of soil nails. To ensure uniform conditions the nails were installed in a soil mass compacted under controlled laboratory condition in a test box. The pull-out capacity of soil nails measured under different matric suctions and overburden pressures were compared among the test results. The matric suctions varied by controlled wetting were monitored by tensiometers while the overburden pressure were varied by hydraulic jacks. The test results showed clearly that the matric suction enhances the pullout resistance.

Keywords: Pull-out resistance, tensiometer, soil nail, matric suction, unsaturated soil, overburden pressure

1 INTRODUCTION

Soil nailing is a widely used slope stabilisation technique using the passive intrusions-soil nails. Soil nailing has many civil engineering applications such as in; abutments, retaining walls, stabilization of slope. Usage of soil nailing was increased in recent years due to its technical and economic advantages.

When the soil mass attempts to move down, a tensile forces mobilized in the intercepted nails will enhance the shear resistance by increasing the normal stress along the potential failure surface while reducing the shear stress to be mobilized for equilibrium. This enhances the factor of safety.

The two key engineering features that should be considered in the design of soil nails are the pullout capacity of the nails generated by interface friction development during various stages of loading and tensile capacity of the nails. Pullout capacity of a soil nail is the parameter with greater uncertainty and it is likely to be affected by overburden pressure, method of installation, shear strength parameters of the soil, grouting pressure, matric suction and dilatancy during pullout.

Conventional design of soil nail does not accounts for the matric suction and dilatancy as a conservative measure. Correct estimation of pullout capacity is critically important in the design of soil nails as over estimation of capacity leads to design failures while under estimation lead to increase in construction cost. A practice adopted widely is to estimate the pullout capacity using an existing formula and to verify it by field pullout tests during the early stages of construction.

The field pullout tests are mostly performed in dry weather conditions where the soil is in an unsaturated state. These testing does not represent the worst case and the measured pullout resistance is higher than that of wet soil condition. In addition to that the prevailing uncertainties in the field like; unknown soil conditions, nail conditions and uncontrolled test conditions cannot be neglected. Hence the behaviour cannot be explained from the parameters derived from field tests.

This paper presents the results on the influence of matric suction and overburden pressure on the pullout resistance of soil nails.

2 LITERATURE REVIEW

Fully instrumented pull-out tests conducted by recent researchers (Gurpersaud et al. 2011;Sivakumar and Singh 2010; Yin and Su 2006; Zhang et al. 2009) have proved that the interface behaviour between soil and different construction materials are influenced by factors such as dilatancy, overburden pressure, matric suction, grouting pressure and soil characteristics.

Experiments performed by Zhang et al. (2009) on completely decomposed granite (CDG) in Hong Kong to study the uncertainties in the measured and actual pull-out capacity of soil nails clearly indicated that matric suction possess the greatest uncertainty.

Studies performed by Su et al. (2008) indicated that the effect of the degree of saturation (matric suction) on soil nail pull-out capacity is significant and should be carefully addressed in the design of soil nailing. Further, Gurpersaud et al. (2011) conducted pull-out tests on nails installed in a compacted sand under the laboratory conditions. The matric suctions achieved in sandy soils were limited (less than 7 kPa). The test results indicated that the post-peak pull-out capacity declines at a much faster rate as the degree of saturation of the soil increases. Hence the decrease in the pull-out capacity was found to be a direct result of the reduction in matric suction. Also, he extended the formula developed by Vanapalli et al. (2010) for estimating the shaft capacity of jacked piles in unsaturated coarse-grained soil to predict the pull-out resistances measured.

Yin et al. (2009) observed that the pullout peak shear stress of the soil nail was less dependent on the overburden pressure when the grouting pressure was low, but the peak shear stress increased with the increasing overburden pressure when the grouting pressure was high.

Ranjan Kumara and Kulathilaka (2016) analyzed results obtained from the pull-out tests on 8 short test nails installed in a slope in Kegalle, Sri Lanka which was stabilized by soil nailing. This analysis showed that the methods currently used for designing of soil nails underestimate the pull-out capacity. Further, by accounting for the unsaturated condition that prevail, possible dilation during pull-out and possible increase of drill hole diameter due to grout pressure a value much closer to the field value can be estimated. Matric suctions were not measured but some estimates were done based on the known ground water table level. Shear strength parameters obtained from two undisturbed samples obtained close to the test nail locations were used to estimate the pullout resistance. The variability of the natural soil profile imposed considerable difficulties in the analysis.

3 METHODOLOGY

3.1 Details of the experimental setup

In this study a uniform soil mass was obtained by compacting a soil at its optimum moisture content with a compaction effort equivalent to standard Procter. This eliminates the material variability and influence of matric suction could be isolated.

Fig.1 presents a detailed section through the test box. Dimension of the Perspex box is 1.3 m x 1.08 m x 0.96 m. A clear distance of 200 mm was kept in all sides to avoid the influence of boundary effects following the suggestion by Zhou et al. (2011). A flexible Polyethene sheet was placed on the vertical side of the Perspex box with lubricating oil between the sheet and Perspex to minimize the friction between the perplex glass walls and the soil.

A residual soil was placed in the test box and compacted in layers of thickness 150 mm with manual compactor (hammer) providing energy equivalent to that of standard Proctor. The compaction process was consistent for all the layers in the test box. According to the in situ density measurements a relative compaction close to 100% had been achieved.

A layer of geo textile was placed on the top of the compacted soil mass and a perforated network of pipes was installed and covered by the coarse aggregates layer of thickness 50 mm. The coarse aggregates were used to facilitate infiltration of water to the compacted soil mass and to prevent damage to the pipe network by surcharge to be applied. The geotextile was used as a separator to prevent the penetration of coarse aggregates into the soil mass. The as compacted soil was unsaturated and possessed a high matric suction. The matric suction within the fill was changed as desired by sending water through the system of pipes or by allowing it to dry, while being monitored through the tensiometers installed. Three tensiometers were placed at different depths in the box to measure the matric suction prevailing at respective location.

Two layers of timber planks and steel plates were placed above the coarse aggregate to distribute the point loads applied from hydraulic jack and to convert it to a uniform surcharge on the nails installed. This arrangement was necessary to obtain a significant surcharge (overburden pressure) on the soil nails in view of the relatively small depth of soil.

3.2 Drilling and installation of soil nails

Soil nails were installed at an inclination of 5^{o} downward to the horizontal. The drill holes were done manually with an auger of diameter 75 mm. The length of the hole was 0.98 m from the face of the box but only the lower 0.78 m was grouted.

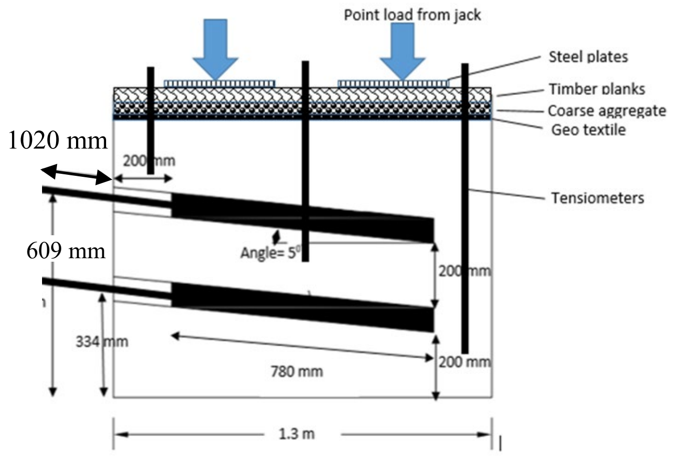

Fig. 1. Details of the Section through the Test Box

The grouting was done at a pressure of 50 kN/m^2. The grouting device used was a sealed PVC cylinder with a 160 mm inner diameter. There were two valves at the inlet, which were used to inject additional cement grout and to apply air pressure. During the pressure grouting process, air pressure valve and the grout outlet valve were opened. A pressure gauge was used to monitor the grouting pressure. Once the grout was used up the valve for injecting grout was opened and fresh quantity was taken in.

Tokyo super ordinary Portland cement and the admixture Flow cable 50 were used in the mix proportion of 200:1 for grouting with a water cement ratio is 0.45. A reinforcement bar of 25 mm diameter Qst Ribbed steel with a tensile strength of 500 MN/m^2 was used as the central nail.

3.3 Instrumentation

The force applied and displacement of the nail during the pull-out test were recorded by the load cell and the dial gauge fixed at the end of the nail (Figure 4). The matric suction was monitored at the top and the bottom tensiometers located near the nail continuously through a data logger.

The miniature tensiometers used for matric suction measurement were developed at Department of Civil Engineering, Kasetsart University, Thailand has a capacity of 0-86 kN/m^2. The High-Air-Entry porous tip in the tensiometer filled with de-aired water. If the matric suction is greater air will enter the system.

The stresses in the soil in the vertical and horizontal directions were measured through a force sensitive resistor (FSR) and Arudino device. Although the surcharge of 60 kN/m^2 and 30 kN/m^2 is applied, the readings obtained from the sensors are 56 kN/m^2 and 26 kN/m^2. The pull-out force was applied by two car jacks assembled in parallel and kept between the load cells and loading frame. With this arrangement it was possible to apply the pull-out load in small increments.

4 SOIL AND MATERIAL PROPERTIES

The characteristics of the soil used to make the compacted fill was determined by basic laboratory tests. According to USCS the soil is silt with high plasticity (MH). Table 1 summarizes the properties of the soil.

Table 1. Properties of Soil

Soil properties	Value/ description
Type of soil	Silt with high plasticity
Optimum moisture content	23.10%
Maximum dry density	1554 kg/m^3
Specific gravity	2.61
Liquid limit	55.80 %
Plastic limit	36.35 %
Plasticity index	19.45 %

The average compressive strength of the grout cubes after 7, 14 and 28 days were 38.4, 51.2 and 56.7 MN/m^2 respectively.

5 PULL-OUT TESTING AND RESULTS

5.1 Pull-out testing

Four tests were conducted on similarly installed nails. First the pull-out of 2 nails were done under near saturation conditions (very low matric suction) under overburden pressures of 30 kN/m^2 and 60 kN/m^2. Thereafter next two nails were pulled out at a higher matric suction of 40 kN/m^2 under similar overburden pressures of 30 kN/m^2 and 60 kN/m^2.

The pull-out testing was done under the guidance from FHWA (1993). There are two methods specified in FHWA (1993); the displacement controlled method and force controlled method. Force controlled method is adapted in this study to evaluate the pull-out capacity.

The jack used to exert the pull-out force was made with two steel plates and welded car jacks in between. This jack was supported by two girders and thread cut in the nail were used to tighten with the supporting frame. Load cell connected with jack is used to measure the load applied. A dial gauge mounted with the nails used for monitoring nail displacement. Fig. 2 shows the pull-out test arrangement.

The pull-out tests were conducted with four cycles of loading and unloading. Initial 2 cycles loading was done to 0.5 DL and 0.75 DL (DL – Design Load). Final cycle was done up to failure. In the final cycle loading was increased in stages to a state until it did not take any further loading.

5.2 Laboratory pull-out test results

The results of the pull-out testing done at different matric suctions and overburden pressures are shown in Fig. 3 and Fig. 4. The measured pull-out capacity in final cycle is summarized in Table 2.

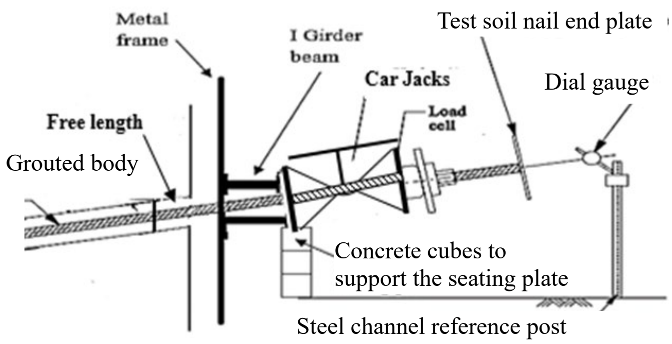

Fig. 2. Pull-out test arrangement

Table 2. Measured Pull-out Capacity

Average Matric suction (kPa)	Overburden pressure (kN/m^2)	Measured Pullout Capacity (kN)
2.4	60	6.55
43	60	9.81
7.67	30	5.84
46	30	9.05

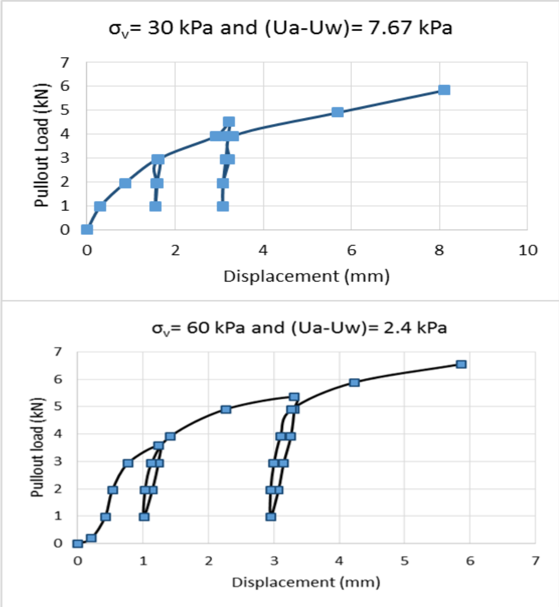

Fig. 3. Pull-out test near saturated state of soil

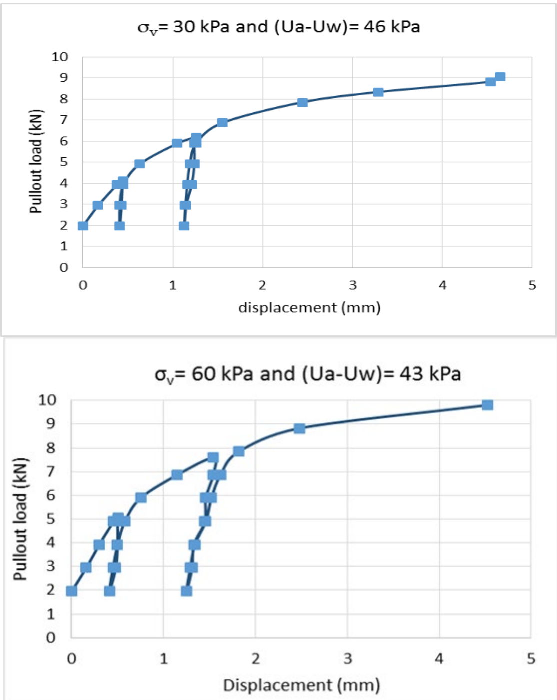

Fig. 4. Pull-out test at a higher matric suction (around 40 kPa)

DISCUSSION AND CONCLUSION

The experimental study demonstrate the influence of matric suction and overburden pressure on Sri Lankan residual soil where the prevailing matric suction are quite high. The decrease in pull-out capacity at a low matric suctions (2.4 kPa, 7.67 kPa) act as an proof to show that matric suction influence the pull-out resistance. The measured pullout resistance at unsaturated state was 1.5 times greater than the nail pulled out near saturated state. Gurpersaud et al. (2011) also observed the pullout capacity in unsaturated sand was 1.3-1.7 times higher than that under saturated state.

Apart from the influence of matric suction, the influence of overburden pressure was clearly observed near the saturated and unsaturated conditions. The peak pullout resistance of soil nails near saturated state under surcharge loading of 60 kPa was higher than surcharge loading of 30 kPa. Similar behaviour was observed at higher matric suction of 40 kPa.

Through this study significant improvement was made in the understanding of influence of matric suction on pullout resistance and necessity to consider the unsaturated parameters in the estimations and design of soil nails.

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