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RESEARCH ARTICLE

Geotechnical Engineering

Effect of degree of saturation on pullout resistance of soil nailing in lateritic soil

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Abstract: Soil nailing is a technique used to reinforce and strengthen the existing ground conditions. This is done by installing closely spaced, passive, structural inclusions known as nails into the soil, and these nails help to improve the overall shear strength of the soil. The nail pullout resistance is the shear stress at the grout-soil interface. The soil nail pullout resistance depends on many parameters. Among the factors influencing the soil nail pullout resistance, the degree of saturation of the soil is an important factor. The pullout resistance may decrease during intense rainfall as the degree of saturation of soil mass changes with the moisture content of the soil. However, verification of pullout tests on soil nail is not conducted under extreme conditions. Hence, the measured pullout resistance may not be a safe parameter for design. As such, in this research study, the effect of the degree of saturation on pullout resistance was studied by conducting a series of laboratory tests using a laboratory pullout box. A specially designed waterproof cap was used to apply back pressure to saturate the soil within the pullout box. Variations of earth pressures close to the grouted nail were observed during the tests. It is evident from the results that the higher the degree of saturation, the lower the pullout resistance. Maximum pullout resistance was observed when the degree of saturation was near the optimum moisture of the soil. When the soil is sufficiently dry, lower pullout resistance was observed due to low bond strength between the grout surface and surrounding dry soil.

Keywords: Degree of saturation, earth pressure, laboratory model setup, pullout resistance, soil nailing.

INTRODUCTION

Soil nailing is an in-situ reinforcement technique that is installed to stabilize soil masses, such as cut and fill slopes, deep excavations, retaining structures, tunnels, etc. The technique used in soil nailing is to reinforce the soil with slender elements such as reinforcing bars, which are called nails; these reinforcing bars are installed into pre-drilled holes and then grouted. These nails are installed at an inclination of 10 to 20 degrees to the horizontal. At present, soil nailing has been widely used to stabilize existing natural slopes as well as cut slopes in Sri Lanka.

Both internal and external failure modes must be considered in the design of soil nailing systems. The internal failure mode consists of pullout failure, tensile failure, and facing failure. Among these, pullout resistance is the key factor in the current soil nailing design (Su *et al*., 2007). Usually, field pullout tests are carried out during the construction stage to verify the design values. There are many factors affecting the soil nail pullout resistance, such as soil type, soil dilatancy, soil shear strength, soil density, grouting pressure, drilling method, degree of saturation, overburden pressure, and matric suction (Burland, 2002; Lazarte *et al*., 2003; Gurpersaud, 2010; Su *et al*., 2010; Gurpersaud *et al*., 2013; Kalehsar *et al*., 2021; Najafi *et al*., 2021). Among the factors influencing the soil nail pullout resistance, the degree of saturation of the soil is important, especially for permanent soil-nailed structures. This is because the degree of soil saturation of the soil mass changes with the variation in ground water levels and weather conditions, and the pullout resistance may drop to a low level during intense rainfall (Su *et al*.,

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2007; Zhang *et al*., 2009). However, the verification of field pullout tests is rarely conducted under extreme saturated conditions. As such, the measured pullout resistance in the field is overestimated by the design value.

Only a few researchers have studied the influence of the degree of saturation on soil nail pullout resistance (Hong *et al*., 2003; Junaideen *et al*., 2004; Chu & Yin, 2005; Pradhan *et al*., 2006; Su *et al*., 2007). These researchers found that the soil nail pullout resistance decreased with the increase in the degree of saturation of soil. Schlosser and Buhan (1991) found that the maximum pullout force was reduced by more than half, when the moisture content increased from the optimum water content to the saturated moisture content. Based on laboratory pullout tests on cement grouted nails in loosely compacted Completely Decomposed Granite fill (CDG), Pradhan *et al*. (2006) found that only the nail–soil interface adhesion was reduced under the high degree of saturation. It was reported that the pullout box used by Chu and Yin (2005), to study the effect of soil saturation on pullout resistance, was simple and it was difficult to achieve a high degree of saturation owing to leakage problems. In addition, in most of the laboratory pullout tests, the overburden pressures were applied to the soil after the soil-nails had been installed, whereas in real-life situations the overburden pressure existed prior to the installation of the soil-nails. As such, in order to overcome these shortcomings and to meet the demand for more comprehensive study on the soil nail pullout resistance, an innovative pullout box was designed and constructed at the Hong Kong Polytechnic University (Su *et al*., 2007). As a result of their research study, the effects of saturation of CDG and overburden pressure on pullout resistance were reported.

However, very few studies have been conducted related to soil nailing in the Sri Lankan context. Generally, the peak shear strength parameters of the soil are used for soil nailing design. However, the effect of soil saturation on the soil nailing design is neglected. In this study, the effect of the degree of saturation of soil on the pullout resistance was studied using a specially fabricated laboratory model setup. A specially designed waterproof front cap and a special tubing arrangement were used to apply the back water pressure to achieve the required degree of saturation. In addition, the variation of earth pressure near the grouted nail during soil nail installation and during pullout tests was studied.

MATERIALS AND METHODS

Pullout box

The effect of the degree of saturation on the pullout resistance of the soil nailing system was evaluated using a laboratory model setup, as shown in Figure 1. One nail was tested at a time to avoid the effects of soil disturbance during the pullout of other nails (Harshani & Priyankara, 2018). The internal dimensions of the model setup used for the study were 600 mm in length, 460 mm in width, and 600 mm in height; these dimensions were sufficient to avoid the boundary effect (Yin & Su, 2006). An additional extension chamber, 280 mm in length, 130 mm in width, and 130 mm in height, was attached to the end of the box, covering the tail of the soil nail, as illustrated in Figure 2. With this chamber, no cavity was developed at the nail tip, and the test length of the soil nail remained constant during the pulling out. A waterproof front cap was provided by means of a triaxial cell at the nail head for the saturation process. Overburden stress was applied using a floor-mounted portal frame and two hydraulic jacks, as depicted in Figure 1. A photograph of the model setup in the laboratory is shown in Figure 3.

Instrumentation and calibration

Five Earth Pressure Sensors (EPS) were installed in the pullout box to monitor the variation of the earth pressure around the soil nail (Figure 2). EPS were used to evaluate the effect of dilation on the resistance to soil nail pullout. The EPS were calibrated initially with an Arduino circuit and a breadboard (Figure 4). Known weights were applied to the pressure pad, and the corresponding analog readings were recorded separately for each pressure sensor. A piece of metal with a cross-sectional area equal to that of the pressure pad was used to place the weights to ensure even application of the weights to the pressure pad. The five sensors showed a similar variation; hence, the average fitted curve was used to obtain the pressure values (Fernando, 2020).

Overburden pressure was applied by using a portal frame with two hydraulic jacks (Figure 1). The applied overburden pressure was measured by using a proving ring attached to the portal frame. A steel plate was placed above the soil surface to achieve uniform deformation of the soil across the pullout box, and two dial gauges were used to measure the vertical deformation.

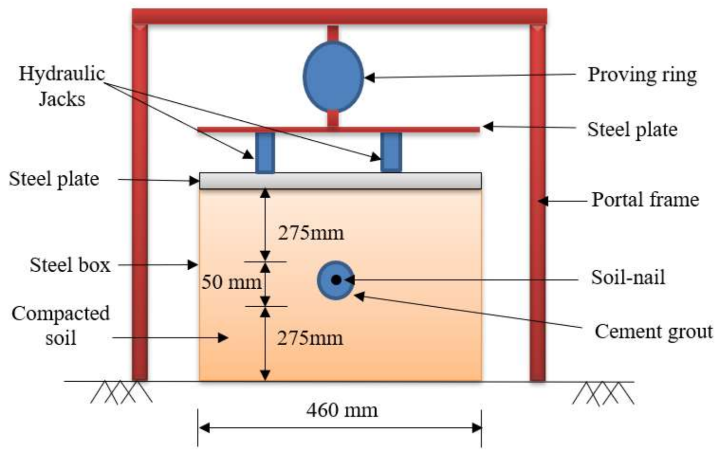

Figure 1: A schematic diagram of the model setup

A hydraulic pullout jack was used to apply the pullout force to the grouted soil nail, and the jack was connected to the nail at the nail head. Hydraulic pressure was applied to the nail in the form of suction so that the nail was pulled out by the jack. A dial gauge fixed at the nail head was used to measure the horizontal displacement of the nail when the pullout force was applied.

Materials

The commonly available lateritic soil was used in this study. The engineering properties of the lateritic soil are given in Table 1. Based on the sieve analysis test results, lateritic soil basically consists of sand, and the soil can be classified as Silty Sand (SM) according to the Unified Soil Classification System (USCS). To determine the degree of saturation of the test specimens, the saturated moisture content of the soil was determined by allowing lateritic soil to saturate over a period of time, and moisture content was measured daily until it became a constant value.

Table 1: Engineering properties of lateritic soil

Property	Value
Specific gravity, $\boldsymbol{G_s}$	2.41
Maximum dry unit weight, $\boldsymbol{\gamma_{d(\max)}}\left(\frac{kN}{m^3}\right)$	17.15
Optimum moisture content, $\boldsymbol{\omega_{opt}}$ (%)	17.6
Liquid limit, LL (%)	53
Plastic limit, PL (%)	44
Saturated moisture content (%)	39.5
Gravel content (%)	0
Sand content (%)	71
Fine content (%)	29

Test Procedure

The general test procedure for soil filling, installation of EPS, applying vertical stress, drilling, grouting, saturation, and nail pullout can be listed as follows:

- The soil was compacted in the pullout box using a rammer to 90% of the maximum dry unit weight. The soil was compacted into layers with a thickness of 50 mm. The amount of soil required for compaction was calculated, and the corresponding amount of water added to the soil.

- Five earth pressure sensors were installed at different levels during the compaction, as shown in Figure 2. Three EPS were installed at the nail head, middle, and tail and placed 40 mm above the grouted nail. To investigate the change of overburden stress over depth during pullout tests, two additional EPS were installed 175 mm above and below the grouted nail (EPS-T and EPS-B), as shown in Figure 2.

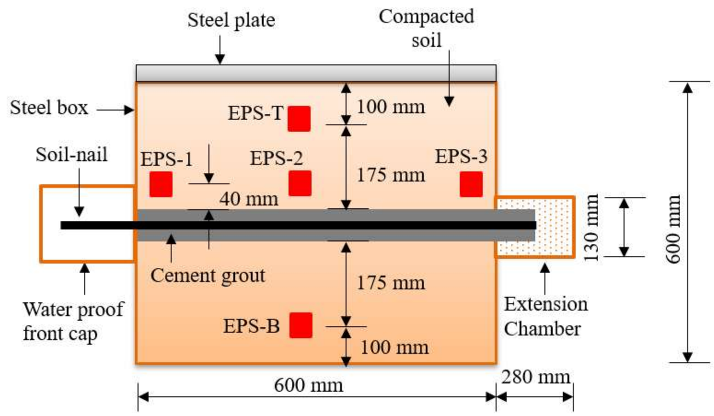

Figure 2: Arrangement of extension chamber, waterproof front cap and instrumentation

- A constant overburden stress of about 48 kPa was applied using two hydraulic jacks (Figure 1 and Figure 3). Both hydraulic jacks were jacked up and down at the same time using a specially fabricated handle to ensure even application of the overburden stress. The applied force was measured by using a proving ring attached to the portal frame. A steel plate above the hydraulic jacks distributes the load uniformly to the jacks. After jacking, the overburden stress was kept constant throughout the experiment.

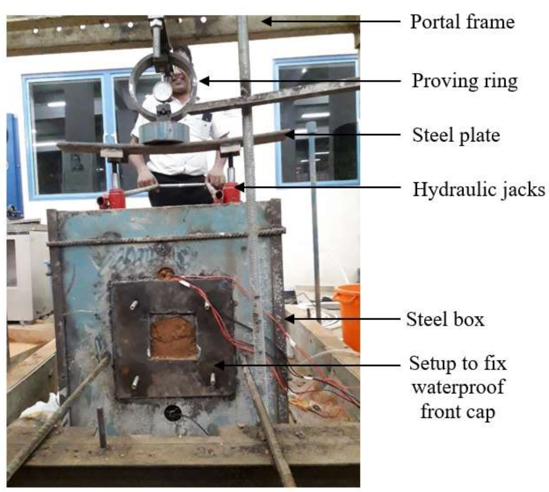

Figure 3: Arrangement of the model setup

- The setup was kept for 24 hours from the application of overburden stress until the soil achieved equilibrium (i.e., EPS readings became constant). A horizontal hole of diameter 50 mm was then drilled using a hand auger (Figure 5). An Arduino setup and a computer were used for the real-time recording of EPS. A steel nail of diameter 10 mm was placed centrically in the drilled hole with the use of centralizers.

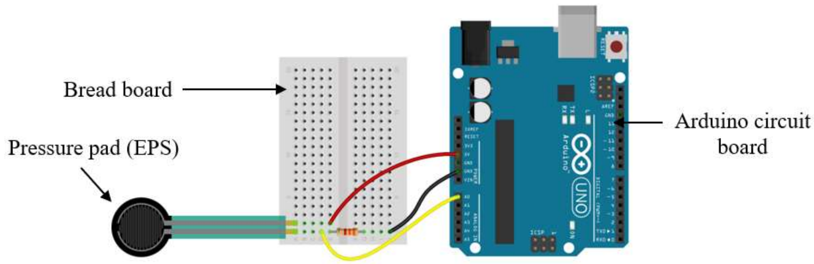

Figure 4: Arduino Circuit arrangement used for calibration

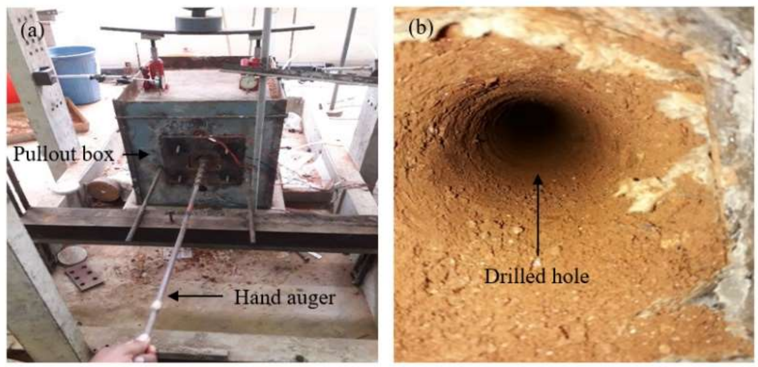

Figure 5: Drilling process (a) drilling a hole using a hand auger; (b) drilled hole

- After the placement of the nail within the drilled hole, grouting was done using a pressure grouting cylinder, as stated in Harshani and Priyankara (2018). A schematic diagram of the grouting device used in this study is shown in Figure 6. Commercially available ordinary Portland cement was used to prepare the grout. The water: cement ratio was kept at 0.5, and the cement was mixed with water and admixtured for a period of 20 minutes using a mechanical mixer. Admixture was used to make the grout flowable, permeable, non-shrinkage, and non-segregate cement slurry. The admixture was added at a rate of 0.5% by weight of cement (Harshani & Priyankara, 2018). Grouting pressure was applied using a compressor and kept constant at 60 kPa throughout all the laboratory experiments.

- Saturation was started three days after the grouting once the grouted nail had acquired adequate strength. The nail head was covered with a waterproof front cap (Figure 2). The waterproof front cap was fixed to a steel plate, which was connected to the pullout box using bolts. To saturate the soil, water flowed into the pullout box through plastic tubes connected to a hole in the side plate. This inlet was divided into 4 lines using T-joints, and 7 openings were provided around the soil nail to facilitate the saturation process, as shown in Figure 7. The openings of the tubes were covered with filter paper to avoid clogging by fine particles. A vacuum pump was used to pump out air from the voids within the soil. A vacuum was applied by connecting the vacuum pump to the valve at the front of the pullout box (near the nail head). Under this suction pressure, the water rose to the top and filled the waterproof front cap. Then, using the air compressor, back-water pressure of about 30 kN/m^2 was applied to the waterproof front cap, which helped to saturate the soil, as shown in Figure 8. The same procedure was repeated, at different time intervals, to achieve different degrees of saturation. Generally, back water pressure was applied in 5-10-minute intervals. A photograph of the pullout box after the application of back pressure is illustrated in Figure 9. Soil samples were collected adjacent to the grouted nail after the pullout test to determine the moisture content of the soil surrounding the grouted nail.

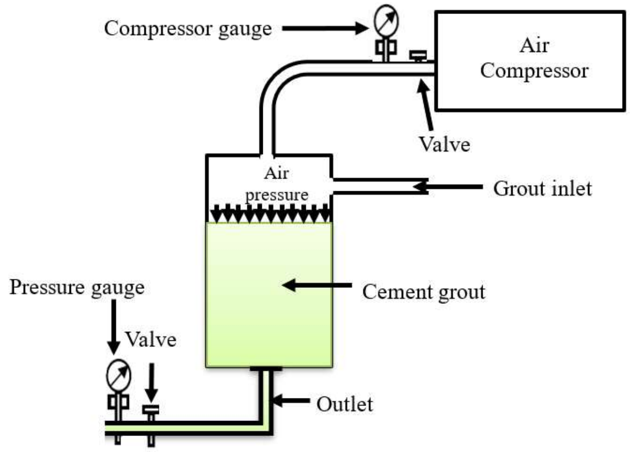

Figure 6: A schematic diagram of grouting device

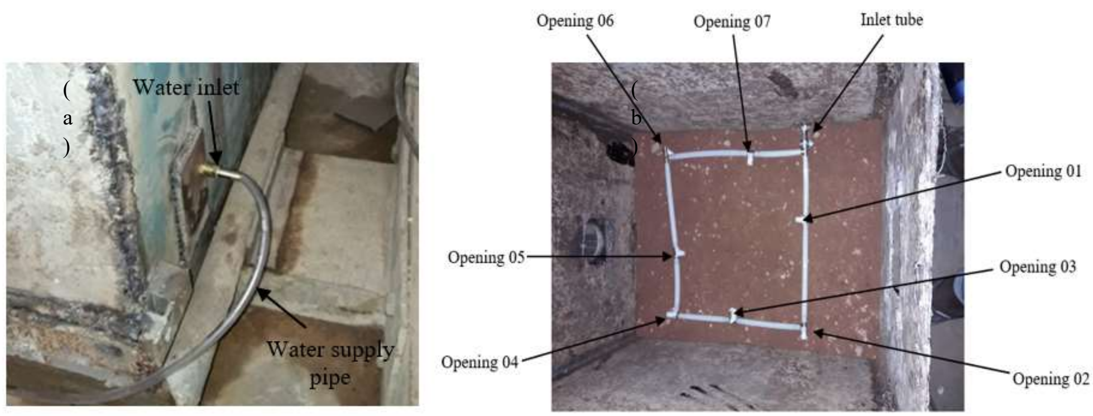

Figure 7: Water tube arrangement in the saturation process (a) water inlet to the pullout box; (b) tube arrangement to saturate the soil (top view)

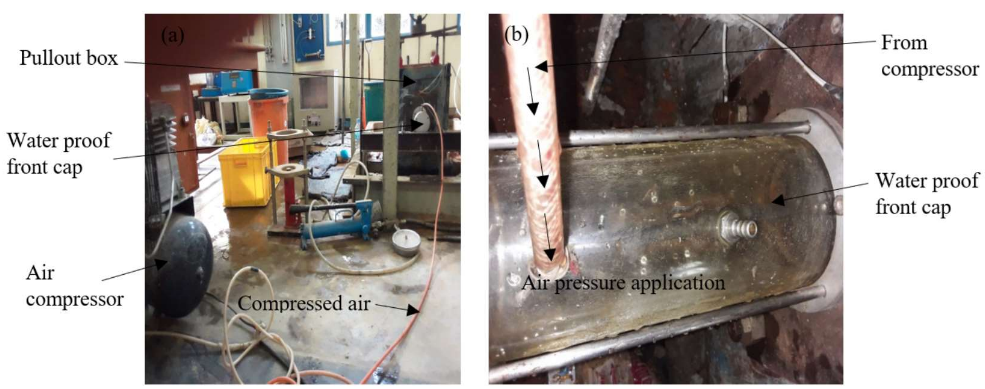

Figure 8: Application of back-water pressure using a compressor (a) complete setup (b) enlarged view of back pressure application

Figure 9: Saturated pullout box after application of back-water pressure

- After the saturation procedure was completed, a pullout test was conducted to determine the pullout resistance of the soil nail. The waterproof front cap was removed, and the nail head was secured to the pullout device with a steel rod that had been additionally welded. The dial gauge was fixed to the end of the nail, and suction was applied to the jack to pull out the nail. The test was conducted under the force control method. Horizontal displacement corresponding to the pullout force was measured using a dial gauge. EPS were used to measure the variation in the overburden stress during the test, which was then recorded in real-time using the Arduino circuit arrangement. A recording software called 'CoolTerm' was used for the real-time recording of earth pressure. The complete experimental setup is shown in Figure 10.

Figure 10: Complete experimental setup

RESULTS AND DISCUSSION

Variation of earth pressure

The variations in earth pressure during the application of overburden stress, drilling, grouting, saturation, and nail pullout are presented in this section.

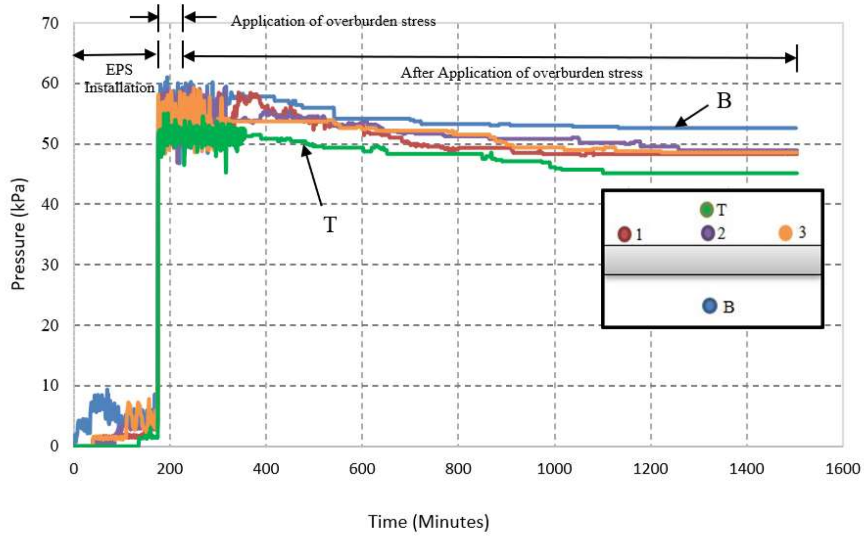

Figure 11: Typical variation of earth pressure during installation and application of the overburden pressure (S_r = 82%)

During the installation of EPS and application of overburden pressure

Figure 11 depicts the earth pressure response against time during the installation of the EPS and the application of the overburden pressure. Since the observed responses are typical for all the experiments, only the results with S_r = 82% (where S_r = degree of saturation) are presented. Small fluctuations in EPS readings were observed during the installation of earth pressure sensors due to soil filling in the pullout box. A significant increment in the earth pressure was observed during the application of the overburden stress. There was a large fluctuation in the earth pressure readings at the initial stage after the application of the overburden stress. This fluctuation was caused by the movement of soil particles that come into contact with the EPS and by the application of different soil weights above the EPS. After approximately 21 h, there was a negligible change in the measured earth pressures, indicating that the vertical stress in the soil was constant and reflected the applied overburden stress. Based on Figure 11, it can be seen that the earth pressure measured by the EPS generally agreed with the applied overburden stress of 44.77 kN/m^2. However, there was a slight difference between the calculated and observed values owing to the variation in the soil density during compaction.

During drilling and grouting

During the process of drilling a hole to install the soil nail, the stress in the soil increases due to the outward pushing of the soil by the drill bit. This behaviour is clearly illustrated in Figure 12; when the drill bit reached the section with the EPS, the earth pressure increased slightly. The earth pressure at Point 1 (i.e., nail head) increased prior to Point 2 (i.e., middle) and Point 3 (i.e., nail tail), and when the drilling progressed further, the earth pressure at Point 2 and Point 3 increased (Figure 12). After the drill bit passed the section of the EPS, the earth pressure dropped significantly due to the release of surrounding stress. There was no significant change in the earth pressure at Point 'B' since the sensor was away from the drill hole. Initially, the earth pressure at points 1, 2 and 3 was approximately 48 kPa, and this increased to approximately 58 kPa at the start of drilling. That is an increment of about 10 kPa. Then there was a sudden drop of nearly 38 kPa, reducing the resultant value of the three sensors to approximately 30 kPa due to the release of surrounding soil stress. Similar behaviour was observed at point 'T', where the earth pressure increased by 5 kPa during drilling and reduced by 10 kPa during the release of stress. This clearly indicates that the soil disturbance during drilling spread only in the upward direction.

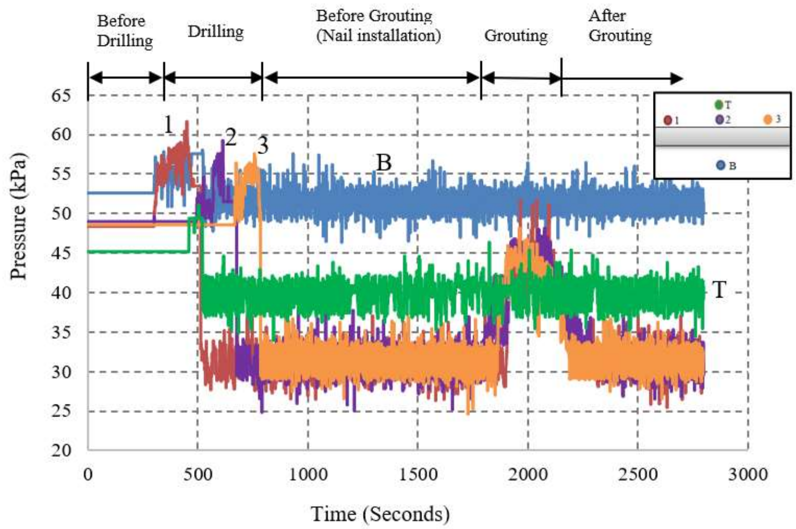

Figure 12: Typical variation in earth pressure during drilling the hole, nail installation and pressure grouting (S_r = 82%)

During the soil nail installation, there was no significant variation of earth pressure in any of the sensors. Grouting was done for nearly 6 min, and during this period, the earth pressure again increased by approximately 15 kPa. However, once the grouting process was completed, the earth pressure dropped to nearly 30 kPa, which means the earth pressure released after grouting was almost 15 kPa. Since the water: cement ratio of the grout was 0.5, the grout contains a significant amount of water. Hence, during pressure grouting, the water in the grout is absorbed by the surrounding soil. As a result, the grout hardens rapidly.

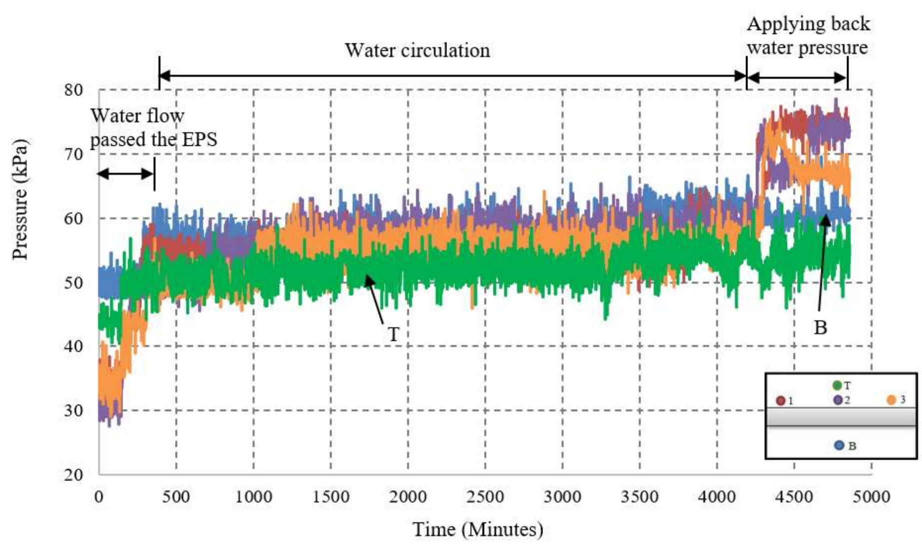

Figure 13: Variation in earth pressure during saturation (S_r = 82%)

During saturation

Saturation was initiated three days after grouting by allowing the grout to harden so that the grouted nail had acquired sufficient strength. The variation of earth pressure during the saturation process is illustrated in Figure 13. Immediately after saturation started, the earth pressure values of all the sensors showed a gradual increment.

The earth pressures in EPS-B and EPS-T showed a sudden increment at first and then continued to increase slowly throughout the saturation period. The earth pressure near the soil nail (EPS-1, EPS-2, and EPS-3) indicated a significant increase in earth pressure when the water flowed passed the sensors. Because of the application of back-water pressure when the waterproof front cap was filled with water, there was a significant increase in earth pressure again near the soil nail. The increase in earth pressure near the nail head (EPS-1) was slightly higher than that of the other two sensors since it was the closest sensor to the waterproof front cap, which applied the back water pressure. After three days of saturation, the water began to fill the waterproof front cap continuously so that the back pressure was applied for a longer time interval than on the previous occasions. This caused the earth pressure values of EPS-1, EPS-2, and EPS-3 to increase significantly because of the continuous back water flow around the nail. It required 2.3 days, 3.3 days, and 8 days to achieve 68%, 82%, and 98% degrees of saturation of the soil within the pullout box, respectively.

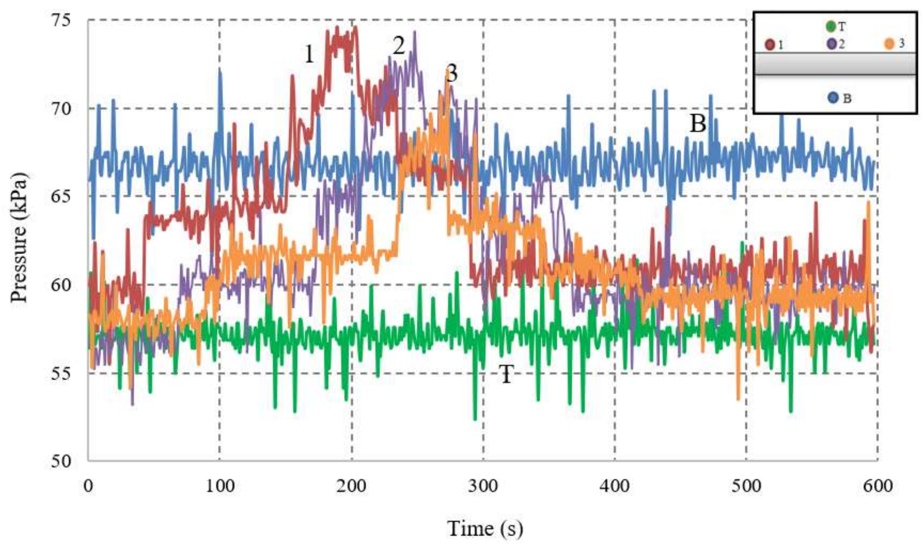

Figure 14: Typical variation in earth pressure during pullout test (S_r = 82%)

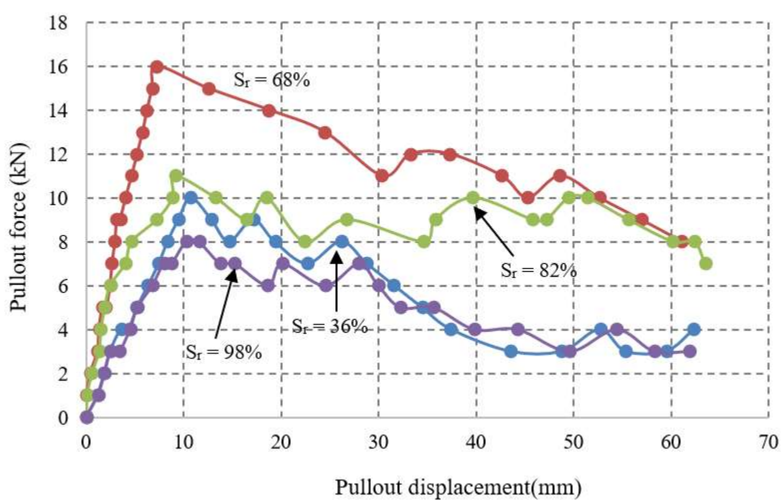

Figure 15: Relationship between pullout force and pullout displacement under different degrees of saturation of the soil

During the pullout test

During the pulling out of the grouted nails, the readings of EPS-1, EPS-2, and EPS-3 increased to their peak values and then decreased with the displacement of the soil nail (Figure 14). The peak value of EPS-1 was higher than that of EPS-2 and EPS-3. This was due to the stress transfer from the nail surface to the soil from the head of the nail to the tail. It is worth noting that the greatest shear displacement was mobilized near the nail head, which decreased towards the nail tail. Earth pressures at EPS-B and EPS-T did not change significantly during the pullout of the nail. Hence, it is evident that the earth pressure changed significantly at or near the soil-grouted nail interface during the pullout test. This behaviour can be identified as dilation of the soil as earth pressure increases during shearing, which depends on soil suction, soil density, and interface roughness. Since soil density and interface roughness remain constant during the pullout, it is evident that soil suction may cause an increase in soil dilatancy. A similar relationship between soil suction and dilatancy was reported by Ng and Zhou (2005). Therefore, it can be concluded that soil dilation is one of the key influencing parameters in the pullout resistance of the soil nail.

Pullout force-displacement behaviour

The relationship between the pullout force and the pullout displacement for different degrees of saturation under constant overburden pressure is shown in Figure 15. Regardless of the saturation level, all the curves exhibit the same pullout force-displacement behaviour. As shown in the pullout force-displacement curves, the average pullout force increased rapidly to reach its peak value and then decreased gradually with displacement.

The analysis of the pullout force-displacement behaviour is illustrated in Table 2. The displacement at the peak pullout force was less than 12 mm in all the experiments. When the soil moisture content was less than the optimum moisture content $(\omega_{opt} < 17.6\%)$, the displacement rate per pullout force, up to the peak value, was 1.0 mm/force. When the soil moisture content was more than the optimum moisture content, the displacement rate per pullout force up to the peak value was approximately 0.5 mm/force. From this, it can be concluded that the rate of displacement per force decreases when the moisture content is greater than the optimum moisture content.

Table 2: Pullout force-displacement behaviour

Moisture content (%)	Degree of saturation (%)	Peak pullout force (kN)	Displacement at peak pullout force (mm)
14.22	36	10	10.75
26.86	68	16	7.24
32.39	82	11	9.10
38.71	98	8	11.55

However, when the degree of saturation was more than 80%, the pullout force initially increased at a rapid rate of 0.5 mm/force with the pullout displacement to nearly 90% of the peak pullout value, and then it continued to increase at a slower rate of 1.5 mm/force until it reached the peak pullout force. In contrast to the above, the opposite behaviour can be observed when the soil is fully saturated. The pullout force initially increased at a rate of 0.6 mm/force until 50% of the peak pullout value was reached, and then it continued to increase at a slower rate of 1.2 mm/force until the peak pullout force was reached. The above explanation clearly illustrates that the rate of displacement per pullout force is highly dependent on the degree of saturation. Furthermore, it can be noted that a maximum displacement of around 63 mm was achieved due to the limitations of the apparatus.

Variation of peak pullout force with the degree of saturation

The variation of peak pullout force over the degree of saturation is illustrated in Figure 16. The shape of the peak pullout force curve versus the degree of saturation was very similar to the compaction curve, where the peak pullout force increases with the degree of saturation until it reaches an optimum moisture content and then decreases when the moisture content is greater than the optimum moisture content. On the contrary, displacement at peak pullout force decreases until the maximum peak pullout force is reached, as shown in Figure 17. The peak pullout force reaches its maximum value when the moisture content is near the optimum moisture content, i.e.,

S_r = 49%. When the soil is on the dry side of its optimum moisture content, water is absorbed by the soil due to higher matric suction. This may cause more contraction of the cement grout, thus reducing the bond strength between the grouted nail surface and the surrounding soil. As such, the peak pullout force is less on the dry side of the soil than that at the optimum moisture content.

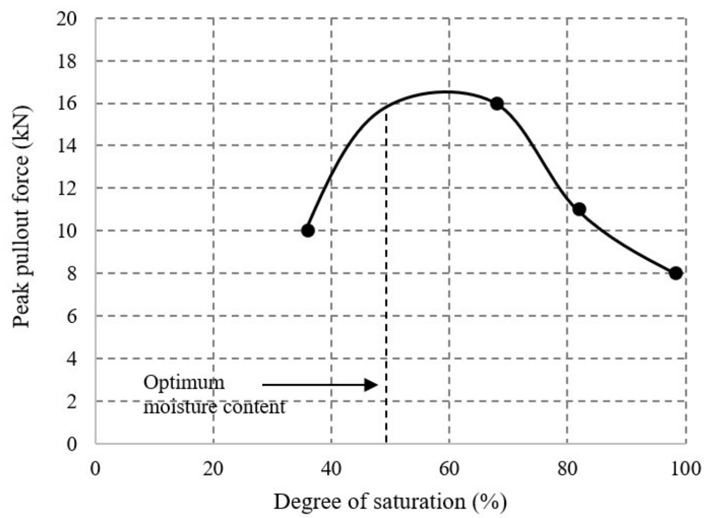

Figure 16: Variation of the peak pullout force over different degrees of saturation

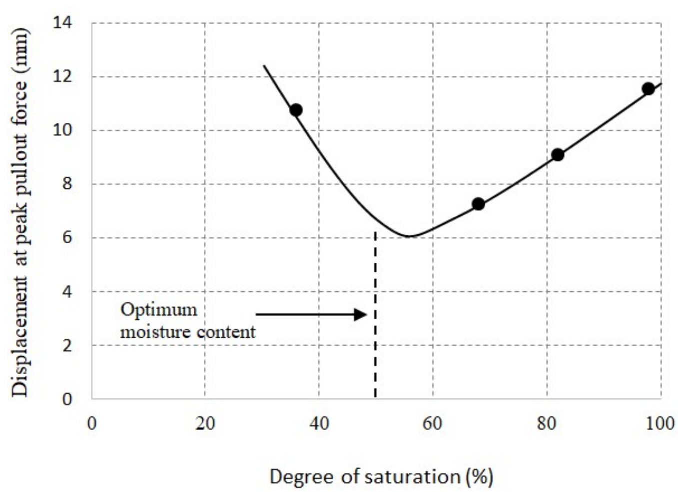

Figure 17: Variation displacement at peak pullout force versus degree of saturation

It is generally believed that when the soil is dry due to higher matric suction, the soil has a higher pullout resistance. However, it was observed that when S_r = 36%, the soil had a lower pullout resistance than that of the others. If the soil is very dry, water within the cement grout is absorbed by the soil due to a higher matric suction. This will lead to the contraction of the cement grout and reduce the bond strength between the grout surface and surrounding soil, resulting in a low peak pullout force. When the moisture content of the soil is more than the optimum moisture content, the apparent cohesion of the soil decreases. As a result, the pullout resistance decreases with an increase in soil moisture content above the optimum value.

Failure mechanism

To determine the failure mechanism of grouted nails during pullout, the surface of the grouted nails was investigated after the tests. Figure 18 illustrates the photographs of the grouted nails after the pullout tests. Even though the hole diameter was only 50 mm, it can be seen that the average diameter of the grouted nail was more than the hole diameter (Table 3), indicating the effect of the grouting pressure. Harshani and Priyankara (2018) reported that the pullout resistance increases with the increase of grouting pressure due to the increase in the diameter of the grouted nail under high grouting pressure. Further, it was observed that the diameter of the grouted nail at the centre was more than that of the nail head and nail tail, irrespective of the degree of saturation. This implies the grouting pressure is concentrated more at the centre than at the nail head and tail. However, the average grouted nail diameter was the same, irrespective of the degree of saturation.

According to the shearing planes illustrated in Figure 18, at different degrees of saturation, the shearing plane had migrated from the interface between the grouted nail and the surrounding soil further into the soil when the soil became saturated. When the soil is fully saturated, a noticeable thick layer of the soil had adhered to the grouted nail surface. This implies the migration of the shearing plane from the grouted nail-soil interface to the soil owing to the decrease of the soil matric suction.

Table 3: Average nail diameter

Degree of saturation (%)	Average nail diameter (mm)
36	55.21
68	55.70
82	54.07
98	55.25

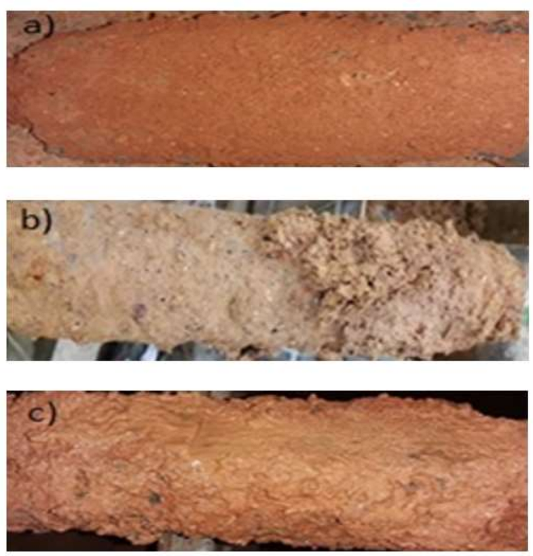

Figure 18: Nail surfaces after pullout test for different degrees of saturation at (a) $S_r = 36\%$; (b) $S_r = 82\%$; (c) $S_r = 98\%$

CONCLUSION

To determine the effect of the degree of saturation of soil on pullout resistance, a series of laboratory tests were conducted using a pullout box by varying the soil moisture content. A specially designed waterproof front cap was used to apply backwater pressure to saturate the soil within the pullout box. Variations in earth pressure near the grouted nail surface were observed during the experiments. Based on the laboratory experimental results discussed above, the following conclusions were drawn:

1. The peak pullout force is highly dependent on the degree of saturation of the soil. The higher the degree of saturation (wet side of the optimum moisture content), the lower the pullout resistance. Similarly, when the soil is sufficiently dry (dry side of the optimum moisture content), water within the cement grout is absorbed by the soil due to higher matric suction, thus reducing the bond strength between the grout surface and surrounding soil. This results in a low pullout resistance.
2. The highest peak pullout force occurs when the moisture content of the soil is close to the optimum moisture content. Similarly, it can be concluded that the highest peak pullout force is within the degree of saturation of soil between 45% and 70%.
3. During the pullout test, the minimum displacement occurs when the moisture content of the soil is near the optimum moisture content. This indicates that the minimum displacement corresponds to the highest peak pullout force.
4. The rate of displacement per pullout force is highly dependent on the degree of saturation of the soil, where the rate of displacement per pullout force decreases when the moisture content is greater than the optimum moisture content.
5. The shearing plane migrated further into the soil from the grouted nail-soil interface when the degree of saturation was high, i.e., more than the optimum moisture content.
6. The stresses within the soil medium near the soil nail interface vary significantly during the grouted nail installation process and during the pullout test. The earth pressure variation near the soil nail interface during the pullout tests indicated that there is a significant effect of soil dilatancy on the pullout resistance of soil nails. Further, soil dilatancy depends on the matric suction of the soil.

It should be noted that the number of tests was limited in this study, and more soil nail pullout tests with more degrees of saturation should be performed to accurately examine the effect of the degree of saturation on pullout resistance. Furthermore, it is necessary to measure the matric suction during the pullout tests to analyse the effect of matric suction on pullout resistance.

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