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Effect of degree of saturation on pullout resistance

Effet du degré de saturation sur la résistance à l'arrachement

Nadeej Priyankara & Arnold Fernando

Department of Civil & Environmental Engineering, University of Ruhuna, Sri Lanka, nadeej@cee.ruh.ac.lk

ABSTRACT: Soil nailing is a technique which is used to reinforce and strengthen the existing ground conditions. This is done by installation of closely spaced, passive, structural inclusions known as nail into the soil and these nails help to improve the overall shear strength of soil. The degree of saturation (S_r) of the soil is an important factor among the factors influencing the soil-nail pullout resistance, especially for permanent soil-nail structures. As such, in this research study, the effect of degree of saturation on pullout resistance was studied by conducting a series of pullout tests using a laboratory pullout box. Especially designed water proof cap was used to apply back water pressure to saturate the soil within the pullout box. Variation of earth pressures close to the grouted nail were observed during the tests. It was evident from the test results that higher the degree of saturation of soil, lower the pullout resistance. Maximum pullout resistance was observed when the degree of saturation is near the optimum moisture content of the soil. When the soil is sufficiently dry, lower pullout resistance was observed due to low bond strength between grout surface and surrounding dry soil.

RÉSUMÉ : Le clouage du sol est une technique qui est utilisée pour renforcer et renforcer les conditions du sol existantes. Cela se fait par l'installation d'inclusions structurelles passives étroitement espacées appelées clous dans le sol et ces clous contribuent à améliorer la résistance globale au cisaillement du sol. Parmi les facteurs influençant la résistance à l'arrachement sol-clou, le degré de saturation (S_r) du sol est un facteur important, notamment pour les structures permanentes sol-clou. Ainsi, dans cette étude de recherche, l'effet du degré de saturation sur la résistance à l'arrachement a été étudié en effectuant une série de tests d'arrachement en laboratoire à l'aide d'une boîte d'arrachement de laboratoire. Un capuchon étanche spécialement conçu a été utilisé pour appliquer une contre-pression afin de saturer le sol à l'intérieur de la boîte coulissante. Il était évident d'après les résultats des tests que plus le degré de saturation du sol est élevé, plus la résistance à l'arrachement est réduite. La résistance maximale à l'arrachement a été observée lorsque le degré de saturation est proche de l'humidité optimale du sol. Lorsque le sol est suffisamment sec, une résistance à l'arrachement plus faible a été observée en raison de la faible force de liaison entre la surface du coulis et le sol sec environnant.

KEYWORDS: Degree of saturation, laboratory model setup, pullout resistance, soil nailing

1 INTRODUCTION.

Soil nailing is an in-situ reinforcement technique which is installed to stabilize the soil mass, such as cut and fill slopes, deep excavations, retaining structures and tunnels etc. The technique used in soil nailing is the soil reinforced with slender elements such as reinforcing bars which are called as nails and these reinforcing bars are installed into pre-drilled holes and then grouted. At present, soil nailing has been widely used to stabilize the existing slopes in Sri Lanka.

In the design of a soil nailing system, both internal and external failure modes have to be considered. The internal failure modes consist of pullout failure, tensile failure and facing failure. Out of that, pullout resistance is a 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 and which depends on the shear strength between grouted soil-nail and surrounding soil. Among the factors influencing the soil-nail pullout resistance, the degree of saturation of the soil is an important factor, especially for permanent soil-nailed structures due to the fact that the degree of saturation of the soil mass changes with the variation of ground water level and weather conditions, and the pullout resistance may drop to a low level during intense rainfalls. However, verification of field pullout tests are very hardly be conducted under the worst condition, *i.e.* saturated condition. As such, the measured pullout resistance in the field is overestimated the design value.

Only very few studied had been done on the influence of degree of saturation on soil-nail pullout resistance (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 degree of saturation of soil. Schlosser et al. 1993 found that the maximum pullout force had been reduced by more than a half when the moisture content was increased from the optimum water content to the saturation moisture content. Based on laboratory pullout tests on cement grouted nails in loose compacted Completely Decomposed Granite fill (CDG), Pradhan et al. 2006 found that only the nail–soil interface adhesion had been reduced under the high degree of saturation. It was reported that pullout box used by Chu & Yin 2005 to study the effect of soil saturation on pullout resistance was a simple one and difficult to achieve a higher degree of saturation due 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 installation of the soil-nails. As such, in order to overcome these shortcomings and to meet the demands 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. 2006). As a result of their study, the effects of saturation of CDG and overburden pressure on pullout resistance had been reported.

However, only very limited research studies has been conducted related to soil-nailing under the Sri Lankan context. Generally, peak shear strength parameters of soils are used for the soil nailing design. On the other hand, the effect of soil saturation on soil nailing design is neglected. As such, in this research study, the effect of degree of saturation of soil on the pullout resistance was studied using especially fabricated laboratory model setup. Especially designed water proof front cap and special tubing arrangement was 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 test was analyzed.

2 MATERIALS AND METHODS

2.1 *Pullout box*

The effect of degree of saturation on pullout resistance of soil-nailing system was evaluated using a laboratory model set up as shown in Fig. 1. One nail was tested at a given time to avoid the effect of soil disturbance during the pullout of other nails (Harshani & Priyankara 2018). Internal dimensions of the model set up used for the research study were 600 mm in length, 460 mm in width and 600 mm in height and these dimensions were enough to avoid the boundary effect (Harshani & Priyankara 2018). Additional extension chamber with 280 mm in length, 130 mm in width and 130 mm in height was attached to the end of the box, covering tail of the soil-nail as illustrated in Fig. 2. With this chamber, no cavity is developed at the nail tip and test length of soil-nail would remain constant during the pulling out. A water proof front cap was provided by means of a triaxial cell at the nail head for saturation process.

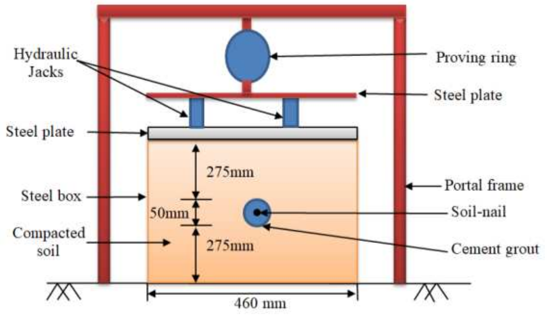

Figure 1. A schematic diagram of model setup.

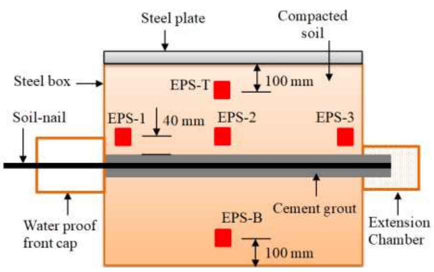

Figure 2. Pullout box and instrumentation.

2.2 *Instrumentation and Calibration*

Five numbers of Earth Pressure Sensors (EPS) were installed in the pullout box to monitor the variation of earth pressure around the soil-nail as shown in Fig. 2. EPS were used to evaluate the effect of dilation on soil-nail pullout resistance. The EPS were initially calibrated using an Arduino circuit and a bread board as shown in Fig. 3. Known weights were applied on the pressure pad and the corresponding analog reading was recorded for each pressure sensor separately. The five sensors depicted a similar variation, hence the average fitted curve was used to obtain the pressure values.

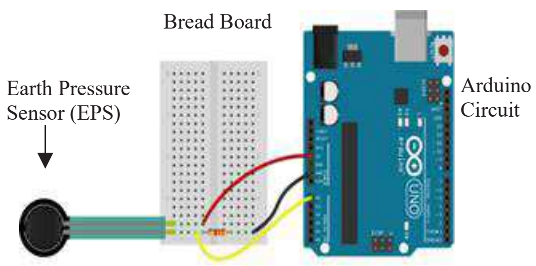

Figure 3. Arduino Circuit arrangement used for calibration.

Overburden pressure was applied by using a portal frame with 2 nos. of hydraulic jacks. The applied overburden pressure was measured by using a loading cell attached to the portal frame. A steel plate was placed above the top soil surface to achieve uniform deformation of the soil across the pullout box and 2 nos. of dial gauges were used to measure the vertical deformation.

A hydraulic pullout jack was used to apply pullout force on the grouted soil-nail and 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.

2.3 *Materials used in the study*

The commonly available lateritic soil was used in this research study. Engineering properties of the lateritic soil is illustrated in Table 1.

Table 1. Engineering properties of Lateritic soil

Property	Value
Specific gravity, G_s	2.41
Maximum dry unit weight $\gamma_{d(max)}$ (kN/m^3)	17.15
Optimum moisture content $\omega_{opt}(\%)$	17.6
Liquid Limit, LL (%)	57
Plastic Limit, PL (%)	31
Saturated moisture content (%)	39.5
Gravel content (%)	0
Sand content (%)	29
Fine content (%)	71

2.4 *Test procedure*

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 a 90% of the maximum dry unit weight. The soil was compacted in layers with thickness of 50 mm. The amount of soil required for compaction was calculated and the corresponding amount of water was added to the soil.
- Five earth pressure sensors were installed at different levels during the compaction as shown in Fig.1. A constant overburden stress of about 48 kPa was applied using 2 nos. of hydraulic jacks. The applied force was measured by using a proving ring attached to the portal frame. Steel plate above the hydraulic jack distributes the load uniformly to the jacks. After jacking, the overburden stress was kept constant throughout the experiment.
- Then the setup was kept for 24 hours from the application of overburden stress until soil achieved the equilibrium (until the EPS readings became constant). Afterwards, a horizontal hole of diameter 50 mm was drilled using a hand auger. Arduino setup and a computer were used for real time recording of EPS data. Steel nail of diameter 10 mm was installed at the center of the drilled hole with the use of centralizers.
- After placement of a nail within the drilled hole, grouting was done using a pressure grouting cylinder as stated in Harshani & Priyankara 2019. The water:cement ratio of 0.5 by weight was used to prepare the cement grout and an admixture was used to made flowable and non-shrinkage cement slurry.

Grouting pressure was kept constant as 60 kPa throughout all the laboratory experiments and it was applied using a compressor.

- Saturation was started three days after the grouting, once the grouted nail had acquired adequate strength. The nail head was covered with water-proof front cap. The water proof front cap was fixed to a steel plate and that plate was connected to the pullout box using bolts. In order to saturate soil, water flowed in to the pullout box by means of plastic tubes connected to a hole in the side plate. This inlet was divided into 4 lines using T-joints and seven openings were provided around the soil-nail to facilitate the saturation process as shown in the Fig. 4. Openings of the tubes were covered with filter papers to avoid clogging of openings with fine particles. A vacuum pump was used to pump out air from the voids. Vacuum was applied by connecting the vacuum pump to the valve at the front of the pullout box (near nail head). Under this suction pressure, water rose to 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 in saturating the soil as shown in Fig. 5. The same procedure was repeated but for different time intervals to achieve different degrees of saturation.
- After the saturation procedure was completed pullout test was conducted to determine the pullout resistance of soil- nail. The waterproof front cap was removed and pulling-out was done with the controlled rate of displacement method and, force and displacement of nail head was recorded. All EPS data during pullout were recorded by a computer and dial gauge readings were recorded manually.

Figure 4. Complete model setup

Figure 5. Saturated pullout box after the application of back water pressure

3 RESULTS AND DISCUSSION

3.1 *Variation of Earth Pressure*

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

The Fig.6 depicts the earth pressure response against time during the installation of EPS and application of overburden pressure. Since the observed responses being typical for all the experiments, only the tests with S_r = 82% is presented. Small fluctuations of the readings can be seen during the installation of earth pressure sensors due to soil filling in the pullout box. A significant increment in earth pressure was observed during the application of overburden stress. After application of the overburden stress, there is a large fluctuation of earth pressure readings at the initial stage. This fluctuation is caused by the movement of soil particles which contact with the EPS and due to the application of different soil weights above the EPS. After about 21 hours, there was a negligible change in the measured earth pressures indicating that the vertical stress in the soil is constant and which reflects the applied overburden stress.

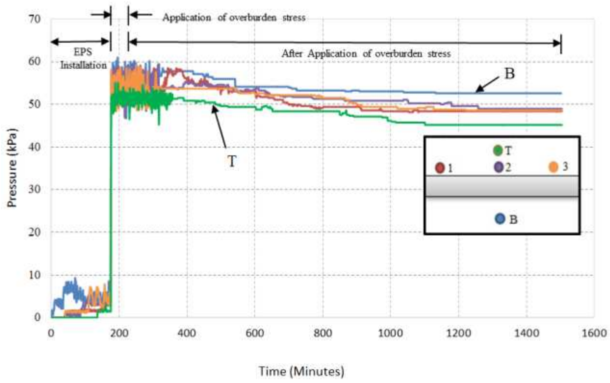

Figure 6. Variation of earth pressure during installation and application of overburden pressure (S_r = 82%)

During the process of drilling a hole to install soil-nail, stress of soil increases due to outward pushing of the soil by the drill bit. This behavior is clearly illustrated in the Fig.7. It can be seen that when the drill bit reached the section with EPS, earth pressure has slightly increased. 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 was progressed further the earth pressure at Point 2 and Point 3 increased as depicted in Fig. 7. After drill bit has passed the section of EPS, earth pressure has significantly dropped due to release of surrounding stress. There is no significant change in the earth pressure at Point 'B' and Point 'T' as both sensors are away from the drill hole, which clearly indicates that soil disturbance during drilling is limited to a narrow region.

Initially the earth pressure at Points 1, 2 and 3 were around 48 kPa and it has increased up to about 58 kPa upon the start of drilling. That is an increment about 10 kPa. Then there is a sudden drop of about 30 kPa reducing the resultant value of the three sensors to around 30 kPa due to release of surrounding soil stress.

During the nail installation there is not any significant variation of earth pressure in any of the sensors. Grouting was done for about 6 minutes and during that period the earth pressure was again increased by about 15 kPa, but once the grouting process was completed, earth pressure has been again dropped to about 30 kPa which means the earth pressure release after grouting was about 15 kPa.

Since water: cement ratio of the grout is 0.5, the grout contains significant amount of water. Hence during pressure grouting, water in the grout is absorbed by the surrounding soil, as a result hardening of the grout occurs rapidly.

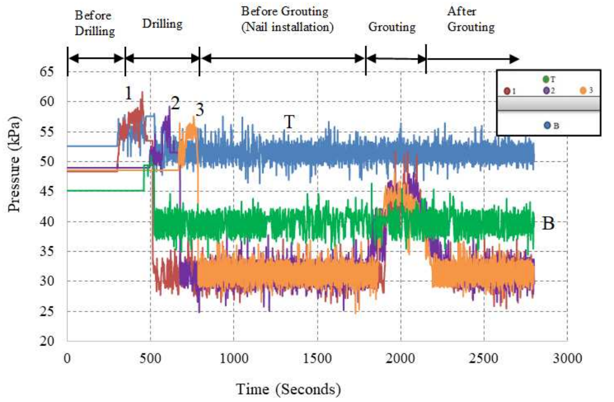

Figure 7. Variation of earth pressure during drilling the hole, nail installation and pressure grouting (S_r = 82%)

Saturation was initiated three days after the grouting as the grout was allowed to harden so that the nail may have acquired sufficient strength. The variation of earth pressure during saturation process is illustrated in Fig. 8. Immediately after saturation started, the earth pressure values of all the sensors show a gradual increment. The earth pressure in EPS-B and EPS-T showed a sudden increment initially 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 increment in earth pressure when the water flow passed the sensors. Due to the application of back water pressure when the water proof front cap was filled with water, there was a sudden slight increment in earth pressure near the soil-nail. It can be noted that increment in earth pressure near the nail head (EPS-1) was slightly higher than that of other two sensors as it is closest to the back flow of water from the nail head. After three days of saturation, the water was starting to fill the water proof front cap continuously, thus the back pressure was applied for a longer interval than the previous occasions. This made the earth pressure values of the EPS-1, EPS-2 and EPS-3 to significantly increase due to the continuous back water flow around the nail.

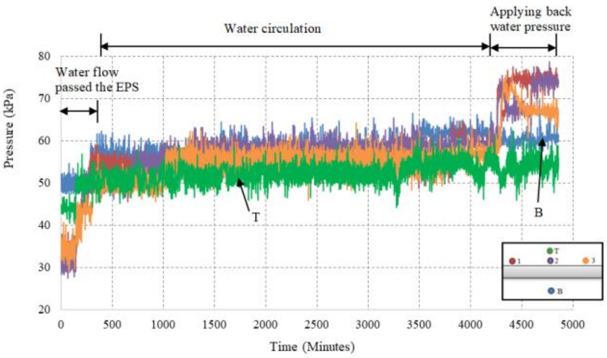

Figure 8. Variation of earth pressure during saturation (S_r = 82%)

During the pulling out of grouted nail, the readings of EPS-1, EPS-2 and EPS-3 were increased to the peak values and then decreased with the displacement of soil-nail as shown in Fig. 9. Peak value of EPS-1 was higher than EPS-2 and EPS-3. This was due to the stress transfer from nail surface to soil from head of the nail to tail. It can be noted that largest shear displacement mobilized near to the nail head and that reduced towards the nail tail. Earth pressure at EPS-B and EPS-T did not change significantly during the pullout of the nail. Hence, it is evident that the earth pressure was significantly changed at or near the soil-grouted nail interface during the pullout test. This behaviour can be identified as dilation of soil as earth pressure increases during shearing and 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. Similar relationship between soil suction and dilatancy was reported by the Ng & Zhou (2005). Therefore, it can be concluded that soil dilation is one of the key influencing parameters in pullout resistance of a soil-nail.

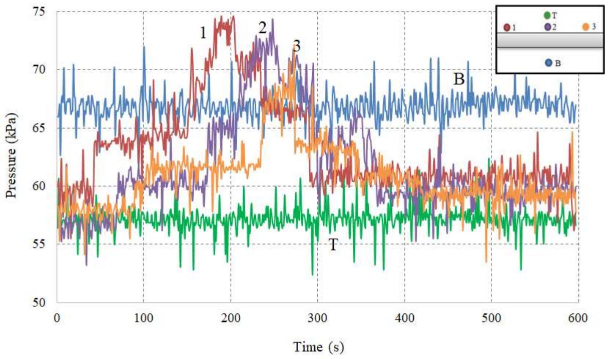

Figure 9. Variation of earth pressure during pullout test (S_r = 82%)

3.2 *Pullout force – Displacement behaviour*

Fig. 10 depicts the relationship between pullout force and pullout displacement for different degree of saturation under constant overburden pressure. All curves show the same pullout force-displacement behaviour irrespective of the degree of saturation. As shown in the pullout force-displacement curves, the average pullout force has been increased rapidly until it reached to the peak value and then it was decreased gradually with the displacement.

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

However, when the degree of saturation is more than 80%, pullout force initially increased at a rapid rate of 0.5 mm/force with pullout displacement to about 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. Similar to the above behaviour can be observed when the soil is fully saturated. Pullout force initially increased at a rate of 0.6 mm/force until 50% of the peak pullout value, 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 rate of displacement per pullout force is highly dependent on the degree of saturation. Further, it can be noted that the maximum displacement of about 63 mm was achieved due to the limitations of the apparatus.

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

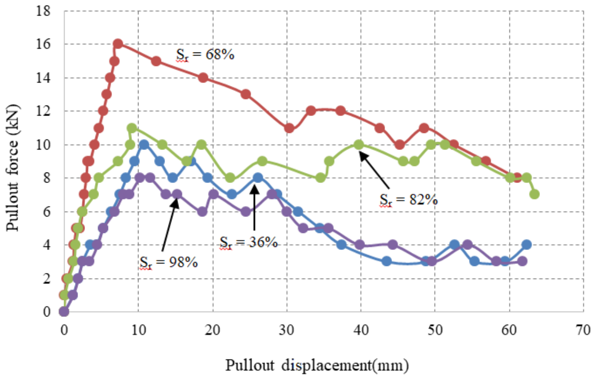

Figure 10. Relationship between pullout force and pullout displacement under different degree of saturation of soil

3.3 *Variation of Peak Pullout force with degree of saturation*

The variation of peak pullout force over degree of saturation is illustrated in Fig. 11. Shape of the peak pullout force versus degree of saturation is very similar to a typical bell shaped compaction curve where peak pullout force increases with the degree of saturation until it reaches to 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 maximum peak pullout force as shown in Fig. 12. It can be noted that the peak pullout force reaches to the maximum value when the moisture content is near to the optimum moisture content *i.e.* S_r = 49%. When the soil is at the dry side of 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 grouted nail surface and surrounding soil. As such peak pullout force is less at dry side than that of optimum moisture content.

Generally, it is believed that when the soil is dry, due to higher matric suction, soil has a higher pullout resistance. However, it was observed that when S_r =36%, soil has lower pullout resistance than that of others. If the soil is very dry, water within the cement grout is absorbed by the soil due to higher matric suction. This will lead to contraction of cement grout and reduce the bond strength between grout surface and surrounding soil, resulting low peak pullout force.

When the moisture content of soil is more than the optimum moisture content, apparent cohesion of soil decreases. As a result, pullout resistance decreases with the increase of moisture content more than the optimum.

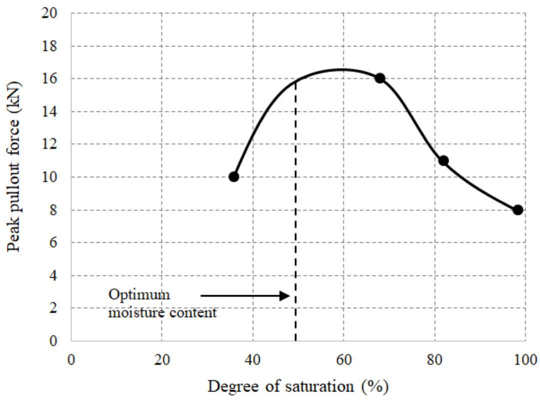

Figure 11. Variation peak pullout force versus degree of saturation

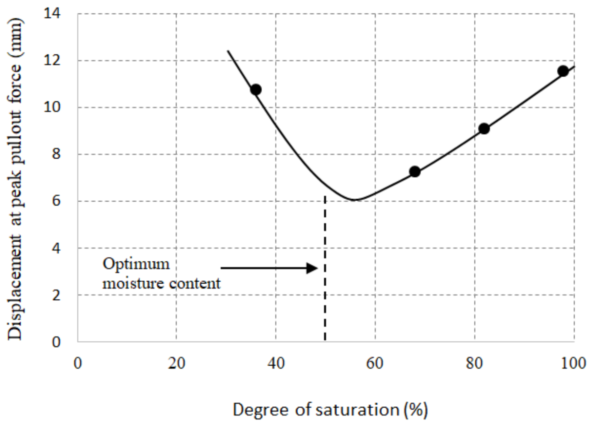

Figure 12. Variation displacement at peak pullout force versus degree of saturation

3.4 *Failure Mechanism*

In order to study the failure mechanism of grouted nail during a pullout, surface of grouted nails was investigated after the tests. Fig. 13, illustrates the photographs of grouted nails after the pullout tests. Even though the hole diameter is only 50 mm, it can be seen that the average diameter of a grouted nail is more than the hole diameter as shown in the Table 3, indicating the effect of grouting pressure. Harshani & Priyankara 2018 illustrated that the pullout resistance increases with the increase of grouting pressure due to the increase of grouted nail diameter under higher grouting pressure. Further, it was observed that grouted nail diameter at the center was more than that of nail head and nail tail irrespective of degree of saturation. This implies that more grouting pressure is concentrated at the center than head and tail. However, average grouted nail diameter was same irrespective of degree of saturation.

According to the shearing planes illustrated in Fig. 13 at different degree of saturation, it can be seen that shearing plane has been migrated from the interface between grouted nail and surrounding soil to further into the soil when the soil become saturated. When the soil is fully saturated, a noticeable thickness of the soil has been adhered to the grouted nail surface. This implies the migration of shearing plane from grouted nail-soil interface to soil due to decrease of soil matric suction.

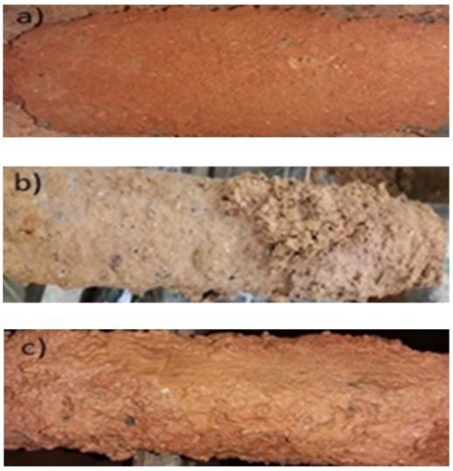

Figure 13. Nail surfaces after pullout tests for different degrees of saturation at (a) $S_r = 36\%$ (b) $S_r = 82\%$ (c) $S_r = 98\%$

Table 3. Average nail diameter

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

4 CONCLUSIONS

In order to study the effect of degree of saturation of soil on pullout resistance, a series of laboratory tests were conducted using pullout box by varying the moisture content. Especially designed waterproof front cap was used to apply back water pressure to saturate the soil within the pullout box. Variation of earth pressures near the grouted nail surface were observed during the experiments.

Based on the laboratory experimental results discussed above, following conclusions can be made.

1. The peak pullout force is highly dependent on the degree of saturation of soil.
2. Higher the degree of saturation (wet side of optimum moisture content), lower the pullout resistance.
3. When soil is sufficiently dry (dry side of optimum moisture content), water within cement grout is absorbed by the soil due to higher matric suction, thus reducing the bond strength between grout surface and surrounding soil resulting low pullout resistance.
4. 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%.
5. The shearing plane is migrated further into the soil from grouted nail-soil interface when the degree of saturation is high, *i.e.* more than the optimum moisture content.
6. The stresses within the soil medium near the soil-nail interface significantly vary 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 number of tests were limited in this research study and more soil-nail pullout tests with more degree of saturation should be performed to examine the effect of degree of saturation on pullout resistance accurately. Further, it is necessary to measure matric suction during the pullout tests to analyze the effect of matric suction on pullout resistance.

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