Analysis of Pullout Resistance of Soil-Nailing in Lateritic Soil

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Abstract: Soil-nailing is an effective slope stabilizing technique, widely used in congested areas. A common problem that experienced in this technique is, the pullout force resulted from field pullout tests are much higher than the theoretical pullout force values calculated for designs. Therefore, this study was done to accurately determine the pullout resistance of soil-nailing by conducting pullout tests on steel bars embedded in compacted laterite soil in a displacement control manner under different overburden pressures and different saturation conditions. Also the effect of grout interface on pullout resistance was evaluated. The experimental results for peak pullout force showed higher values compared to theoretical values and a multiplication factor within a range of 2 - 2.7 was resulted for theoretical values with a soil-nail interface. This difference is significant with a grout interface and the multiplication factor increases up to a range of 4.8 - 6. The test results were compared to the numerical results gained from a two-dimensional PLAXIS model. The numerical results were similar with the experimental results and a PLAXIS model can be used to evaluate the pullout resistance in soil nailing. An increase of pullout resistance was resulted with the increase of overburden pressure and lower pullout forces were resulted under higher saturation conditions.

Keywords: Soil nailing, pullout resistance, laboratory model, numerical model, overburden pressure, degree of saturation

1. INTRODUCTION

It is a challenge in geotechnical engineering to stabilize steeper larger slopes in congested areas and soil-nailing is an effective slope stabilizing technology which can be used in congested areas with a low cost, less working area and with fast construction (Powell and Watkins, 1992). The behavior of a soil-nailed wall is much advanced and several researches (Pradhan et al., 2006; Milligan and Tei, 1998) have been studied the behavior of a nailed-soil mass.

A laboratory setup was prepared by Pradhan et al. 2006 for one such study with a sand tank of 2 m × 1.6 m ×1.4 m in length, width and height, providing 5 holes with 300mm center to center spacing for nail installation. Furthermore, a portal frame structure was placed as a loading frame to supply a surcharge load to the apparatus and nail pulling during loading was done by a pullout jack attached to the nail end that extend out from the test box. Also, the tests were done under different overburden pressures and it was concluded that the pullout force increases with the increase of overburden pressure. Gurpersaud et al., 2010 installed Linear Variable Displacement Transducers (LVDT) to measure displacement and applied force and recorded through a Data Acquisition System (DAS). Pressured water bladders were used by Miles 2011, for the application of overburden pressure. All these studies were to evaluate the variation of pullout resistance by varying the physical properties of the system.

However there is no any advanced quantitative analysis regarding the stress developed on the soil-nail interface. A common problem that experienced in geotechnical engineering is that the pullout force resulted from field pullout tests are much higher than the theoretical pullout force values calculated for designs. Therefore, this study was conducted to compare experimental results with the theoretical values and build up a relationship to accurately determine the pullout force in soil nailing in order to perform cost effective designs. Generally, theoretical pullout force values are calculated based on the equation,
where $c', \phi'$ are effective shear strength parameters (cohesion and friction angle) of surrounding soil, $d$ is the nail diameter and $l$ is the nail length. Therefore a bond coefficient $f_s$, was introduced to the theoretical pullout force values to be equal to the experimental pullout force values. Then field pullout force ($f_{\text{field}}$) can be determined as,

$$f_{\text{field}} = f_s \times \pi dl(c' + \sigma' \tan(\phi'))$$  \hspace{1cm} (2)

Determination of this bond coefficient $f_s$ was done from this research study as a solution to accurately determination of the theoretical pullout resistance. Hence, objectives of the research study can be summarized as:

1. Determination of effect of overburden pressure, degree of saturation and grout interface between nail and soil on pullout resistance using a laboratory model setup.
2. Determination of pullout resistance by numerically (using PLAXIS software).
3. Determination of theoretical pullout resistance accurately by introducing a bond coefficient.

2. METHODOLOGY

2.1. Material selection and determination of basic soil properties

Commonly available Laterite soil was selected as the soil type and the basic soil properties were determined and depicted in Table 1. Soil type was classified as poorly graded sand (SP) with little or no fines according to USCS (Unified Soil Classification System).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Limit (%)</td>
<td>67</td>
</tr>
<tr>
<td>Plastic Limit (%)</td>
<td>50</td>
</tr>
<tr>
<td>Plasticity Index (%)</td>
<td>17</td>
</tr>
<tr>
<td>Optimum Moisture Content (%)</td>
<td>22</td>
</tr>
<tr>
<td>Maximum Dry Unit weight ( kN/m²)</td>
<td>16.2</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.70</td>
</tr>
<tr>
<td>Coefficient of Uniformity ($C_u$)</td>
<td>4.13</td>
</tr>
<tr>
<td>Coefficient of Curvature ($C_c$)</td>
<td>1.38</td>
</tr>
</tbody>
</table>

In field application of soil nailing, 25-32 mm diameter bars are used. However, in model studies it is not practical to use such diameters compared with mould dimensions. Meethananda et al. evaluated the effect of plain and deformed bars of 10mm and 12 mm diameter and they have concluded that there is no much increase in pullout force compared to the increase in nail diameter. Further, there is a significant increase of pullout force of deformed bars compared to plain bars. Therefore, deformed ture steel bars with 10 mm diameter were selected as nails to be inserted in to the soil mass for this study.

2.2. Mould preparation

A steel box with internal dimensions of 610 mm × 480 mm × 600 mm was used as the model setup. Laterite soil was compacted at the optimum moisture content in 50 mm layers. After soil were compacted up to 150 mm height, reinforcement bars were placed for nail alignment and then filling and compaction were proceeded for next 150 mm thickness. Nails were placed with 150 mm spacing simultaneously with soil filling. A 50 mm distance was kept between the nail and the back boundary of the box to avoid end effects. A pullout jack was fixed to the free end of the nail to pull the nail outwards. The laboratory experimental setup is shown on the Figure 1.
2.3. Instrumentation and testing procedure

Overburden pressure was applied to the box by jacking two hydraulic jacks fixed to a portal frame and monitored by a load cell. A dial gauge was fixed to the nail to monitor the horizontal displacement of the nail during pulling. Pulling out of the nail was done by a pullout jack and the hydraulic pressure required in nail pulling was recorded from a pressure gauge connected to the jack. Before proceed the test, a calibration test was done to determine the force corresponds to the recorded fluid pressure. The pullout test was conducted in a displacement controlled manner by jacking the pullout jack. The top most nail was tested first. The horizontal displacement of particular nail was monitored up to a distance of 25 mm and test was terminated after nail was failed. That means no more pressure increases with nail movement. Series of pullout tests were conducted under different overburden pressures as well as different saturation conditions.

In order to study the effect of grout interface on pullout resistance, 3 number of holes with 25 mm diameter were created with 150 mm spacing during the soil compaction. After that, nails were placed at center of the hole with the support of stands and cement grout were injected. Pullout tests were conducted 14 days after grout injection as cement achieved 75% of the strength after 14 days.

2.4. Numerical Analysis

Numerical modeling was done using PLAXIS software in order to simulate the conditions of the laboratory model set up for a soil-nail interface to obtain the pullout resistance. All geometric properties were drawn and the properties of Laterite soil was assigned for fill material. Model was analyzed from Mohr-Coulomb failure criteria. The fixed boundary condition at the base (restricted horizontal and vertical movement) while pin boundary condition at the back boundary (free vertical and restrict horizontal movement) of the setup. Furthermore, a prescribed overburden pressure was assigned to the input geometry. The input geometry of the model is shown in the Figure 2. The mobilized interface forces were taken from the model for each given displacement.

By introducing a separate soil-nail interface, frictional surface between nail and soil was modeled. Pullout forces and interface forces were obtained by applying subscribed displacements to the free end of the nail in the geometry. Horizontal displacements were varied up to 5 mm with 1 mm interval and the frictional stress developed at the soil-nail interface was resulted from the model analysis. The model was run varying the overburden pressure from 20 kN/m² to 80 kN/m² and for each overburden pressure, behavior of 3 nails were analyzed. First, the prescribed displacement was given to the top most nail, then for the middle nail and finally for the bottom most nail. The analysis was done in Staged Construction Mode and the stresses at each phase were resulted from the analysis.
3. RESULTS AND DISCUSSION

3.1. Variation of pullout test with nail displacement

The typical variation of pullout force with the nail displacement is shown in the Figure 3. Irrespective of the nail location, all nails illustrates the same behavior. It can be seen that pullout force increased up to a peak value, and then reduced with nail displacement and reached to a constant value. It state in a constant value for a while and decreased. After this peak pullout force value the nail has already loosen from the soil mass and it comes out with a lower force compared to the peak value. This peak pullout force can be considered as the maximum pullout resistance that mobilized on the interface. Nail 1, 2, 3 represents top, middle and bottom nail respectively.

Figure 3 Pullout force variation of a soil nail (under a surcharge of 60 kN/m²)

Both experimental and theoretical peak pullout forces values calculated based on Eq. (1) were increased with the increase of overburden pressure as illustrated in Figure 4. It is very clear that theoretical pullout resistance is much lower than that of experimental results. In order to identify the difference, a multiplication factor was introduced to theoretical pullout force so that equals to the experimental results and it was found that it lies within a range of 2.0 - 2.7.
3.2. Effect of degree of saturation on pullout resistance

In order to study the effect of soil saturation on pullout resistance, pullout tests were conducted for 60 kN/m² under two saturation conditions and results are presented in Table 2.

<table>
<thead>
<tr>
<th>Degree of saturation (%)</th>
<th>Pullout Force (kN)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Nail 1</td>
</tr>
<tr>
<td>84.33</td>
<td>1.87</td>
</tr>
<tr>
<td>93.21</td>
<td>1.44</td>
</tr>
</tbody>
</table>

It can be observed that with the increase of degree of saturation, pullout force gradually decreases. This is mainly due to reduction of shear strength parameters over soil saturation. This is a clear indication that during the design of soil-nails, it is important to use residual shear strength parameters rather than peak shear strength parameters to calculate the pullout resistance.

3.3. Effect of cement grout on pullout resistance

In soil-nail stabilized slopes, generally nails are placed in concrete/cement grouted holes. Therefore, the most influencing factor on soil-nail pullout resistance is soil-grout interface. In order to study the effect of soil-grout interface, two pullout tests were conducted by introducing a grout interface between soil and nail. A 25 mm holes were generalized in the soil mass during compaction and nails were placed at the center of cement grouted nail. Since cement/concrete achieves 75% of compressive strength after 2 weeks time, pullout tests of these specimens were conducted after two weeks of grout placement and results are summarized in Figure 5.
3.4. Comparison of numerical results with the experimental results

The shear stress variation of the soil nail interface along the nail length was resulted from PLAXIS model and it shows that the mobilized shear stress is not a constant value along the nail length. Its variation is shown in the Figure 6 and a peak value is resulted at a point closer to the nail corner inside the mould. Not at the free end of the nail. This point of mobilization of maximum shear stress is an important in evaluation of the failure plane of the model.

![Figure 6 Shear stress variation of an interface along a nail](image)

The frictional force values at the interface for nail 1, 2 and 3 at overburden pressures of 20 kN/m², 40 kN/m², 60 kN/m² and 80 kN/m² were resulted from the model by applying prescribed displacements to the nail. These numerical results were compared with the experimental results and the comparison is shown in the Figure 7. It shows that both results are almost equal. Since these numerical results and experimental results are almost equal, the range of 2 – 2.7 for multiplication factor that was introduced in Eq. (2) is validated from the numerical analysis.

![Figure 7 Comparison of experimental and numerical results](image)

Also the behavior of the soil strata during nail pulling was resulted from PLAXIS. Soil deformation after pulling of top most nail up to a horizontal displacement of 25 mm was resulted is shown in the Figure 8 and it shows that soil layers has disturbed to a considerable level with the withdrawal of the top nail. In experimental results, it was observed that there is a decrease in peak pullout force of Nail 2 compared to the peak pullout force in Nail 1 although it need to be higher in theoretically, with the increase of fill height by 150 mm. The same behavior was observed by evaluating the experimental results under different overburden pressures and the pullout forces of bottom most nails were showed scattered variations with the overburden pressure although it need to show a linear variation. The reason behind these observations is the disturbance of soil strata around Nail 2 with the pulling out of Nail 1. Therefore it can be concluded that pulling of the top nail has caused for loosen of the interface bonding of the bottom nails. The same behavior was observed in the results of Nail 3 with the loosening of soil by pulling out of Nail 2 and these numerical analysis provides the proof.
CONCLUSIONS

From the test results it can be concluded that the pullout force increases with the increase of overburden pressure and therefore, the fill height up to the nail interface and the externally applying surcharge need to be co-related in the design of soil-nail structures. Also pullout force decrease with the increase of degree of saturation due to the lower shear strength in wet soil and it is a clear indication that it is important to use residual shear strength parameters rather than peak shear strength parameters to calculate the pullout resistance during the design of soil-nail structures.

It is clear that the field pullout force values are considerably higher compared to the theoretical pullout force values calculated based on Eq. (1) and therefore multiplication factor of 2 – 2.7 can be introduced to the theoretical values in order to be equal with the field values for a soil-nail interface. These values can be incorporated in soil-nail designs to make them cost effective.

Furthermore, it shows that the grout interface is the most influencing factor for the pullout resistance of a soil nail and it causes for a significant increase of pullout force by making a strong bonding between the nail and the surrounding soil. Grout injection to the soil has caused for filling of voids in the surrounding soil and hardened to enhance the bonding of the nail, with the soil resulting higher pullout resistances.

REFERENCE


