# Experimental Study on the Influence of Drillhole Roughness on the Pullout Resistance of Model Soil Nails

Cheng-Yu Hong[1]; Yi-Fan Zhang[2]; Jun-Wei Guo[3]; and Geng-Ying Li[4]

**Abstract:** Pullout resistance of cement-grouted soil nails is a key factor affecting the safety conditions of retaining walls, slopes, and excavations. The mobilized frictional resistance at the interface between soil nails and surrounding soils depends on various parameters such as saturation ratio, water content, grouting under gravity or pressure, etc. The interface roughness condition between soil nail and soil is a critical factor but difficult to control in both laboratory and field owing to technical difficulties in creating a rough drillhole surface. The present study focuses on the pullout behavior of model soil nails with different interface roughness conditions in the laboratory to establish quantified correlations between frictional resistance and roughness angles of internal drillhole surface. Cross-sectional shapes of internal drillhole surfaces were created using four plastic rods with various shapes of external threads (four different values of roughness angles). Measured peak values of pullout resistance of soil nails with rough drillhole surface were compared with the soil nails with smooth drillhole surface. The present test results were verified with a previous analytical model, which considered the soil dilation to be an important factor influencing the pullout resistance of soil nails. Test results also indicate that the peak pullout resistance increases almost linearly with an increase in roughness angles. In addition, the pullout resistance values decrease approximately linearly with an increase in pullout displacement after peak pullout resistance is approached. The soil-nail diameter values of the soil nails with rough drillhole surfaces expanded substantially after being pulled out of the ground. This leads to a substantial increase in pullout resistance of soil nails. **DOI: 10.1061/(ASCE)GM.1943-5622.0000491.** 

**Author keywords:** Cement-grouted soil nails; Roughness angle; Pullout resistance; Pullout tests.



## Introduction

Soil nailing has been a popular technique for the stabilization of different geotechnical engineering structures for a few decades. Most theoretical and experimental investigations of the pullout behavior of cement-grouted soil nails have focused on the quantified analysis of pullout resistance associated with different parameters. These typical analytical and experimental findings show that the soil-nail pullout behavior is complex particularly in a real field, depending on a number of critical parameters such as grouting pressure, water content and saturation ratio of soils, roughness conditions of soil-nail surfaces, overburden soil pressure, etc. (Hong et al. 2013; Su et al. 2007, 2008; Yin et al. 2009; Yin and Zhou 2009; Zhang et al. 2009; Zhou et al. 2012).

A large number of theoretical investigations with respect to the pullout resistance of soil nails placed in soils have been conducted under different testing conditions. Most of these studies were related to the analytical derivations of the pullout resistance relationships against pullout displacement for two-dimensional and three-dimensional reinforcements. For cement-grouted soil nails, owing to the possible existence of grouting pressure, mathematical models may involve correlation between grouting pressure and pullout resistance of soil nails (Hong et al. 2013; Yin and Zhou 2009; Zhou et al. 2011, 2012). In these theoretical models, it is normally difficult to account for the potential influence of drillhole roughness on the frictional resistance of soil nails. However, by using a model parameter such as dilation angle (Wang and Richwien 2002), the effect of the surface roughness of drillholes may be taken into account in a new mathematical model by defining the frictional coefficient at the interface between soil and soil nail. Related investigations have been carried out by a number of researchers (Wang and Richwien 2002; Yin et al. 2011; Yu and Houlsby 1991; Zhou and Yin 2008).

Laboratory tests provide ideal testing conditions in which many uncertain factors resulting from complex ground conditions in a real field can be completely prevented (Su et al. 2006; Yeung et al. 2007; Yin and Su 2006). Past experimental results reveal the systematic effect of many critical parameters on the interaction behavior between soil and soil nails in pullout tests. Presented a typical study on the effect of smooth and rough nail surfaces on the pullout resistance of soil nails embedded in sand. A numerical approach is also provided for theoretical analysis of the interaction behavior between soil and soil nail. It is found that, among all critical factors, the surface roughness of a drillhole plays a significant role and leads to substantial rise of peak frictional resistance of soil nails. The main reason for the increase of pullout resistance is that the rough drillhole surface results in a substantial expansion effect of soil surrounding a soil nail during pullout, leading to more normal stress around the soil nail and therefore a higher pullout resistance. However, experimental findings regarding the quantified effect of drillhole roughness on the pullout resistance of soil nails are limited owing to the technical difficulties for creating rough drilhole surfaces in both the laboratory and the field, where there are real, complex ground conditions.

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This paper presents a typical investigation on the pullout resistance of cement-grouted soil nails associated with the systematic variations of cross-sectional shapes of rough drillhole (or soil nail) surfaces. This involved two typical cross-sectional shapes of threads, including triangular and rectangular. From pullout test results and related experimental observations, quantified analysis of pullout resistance of soil nails is presented to improve the understanding of pullout behavior of soil nails grouted inside drillholes with rough surfaces.

## Pullout Test Setup of Model Soil Nails in Laboratory

### Soil Properties

Conventional laboratory tests were carried out to evaluate the parameter values of soil used in the pullout box. The soil before compaction was relatively loose and the related water content range was between 12 and 14%. The light compaction tests conducted using a 2.5-kg hammer show that the optimum water content and the maximum dry density of soil were 17.6% and 1.72 mg/m$^3$, respectively. All soil in the pullout box was placed and compacted in three layers. The main control parameter in the compacting process was the water content and the total weight/mass of the soil in each layer (calculated by the desired soil volume of each layer, density of soil, and the optimum water content). First the water was added into the relatively dry and loose soil to approach the optimum water content. Then the soil was compacted up to 95% of the maximum dry density in each layer. Sieving test results indicate the soil included 7.8% gravel, 90.9% sand, and 1.3% silt and clay, and the calculated coefficient of uniformity $C_u$ and coefficient of curvature $C_z$ are 12.3 and 1.1, respectively. Therefore, the soil was classified as well-graded sand according to the ASTM soil classification system. All these parameter values are shown in Table 1.

**Table 1.** Properties of Soil Placed in Pullout Box

| Parameters | Unit | Values |
|---|---|---|
| Specific gravity, $G_s$ | — | 2.66 |
| Maximum dry density, $\rho_{d\max}$ | mg/m$^3$ | 1.72 |
| Optimum moisture content, $w_{opt}$ | % | 17.6 |
| Gravel | % | 52.7 |
| Sand | % | 27.3 |
| Silt and clay | % | 20 |
| Coefficient of uniformity, $C_u$ | — | 12.3 |
| Coefficient of curvature, $C_z$ | — | 1.1 |

### Surface Roughness of Drillholes

Drillhole surfaces of soil nails in the present laboratory pullout tests involved two typical cross-sectional shapes, including triangular and rectangular thread shapes. Fig. 1 shows photos of plastic thread rods used in the present tests for the creation of different shapes of threads. These threaded rods with triangle and rectangle cross-sectional shapes are designated Type T (triangle) surface and Type R (rectangle) surface, respectively. The Type T and Type R surfaces consist of three subtypes (namely Type T1, Type T2, and Type T3) and two subtypes (namely Type R1 and Type R2), respectively. These surfaces differ substantially in dimensions of thread height and spacing. Fig. 2 shows the detailed dimensions of threads for different types of drillhole surfaces. A smooth rod in external diameter 40 mm and length 300 mm was used for the creation of the smooth drillhole surface, namely Type S0. The rough drillhole surfaces include five basic subtypes with different thread spacing and heights. The thread spacing of the Type T surface is 8 mm and the heights of threads vary from 2, 4, and 6 mm for Type T1, Type T2, and Type T3 surfaces, respectively. The thread spacing for Type R1 and Type R2 surfaces are 10 and 8 mm, respectively, and the related thread height is 8 mm. External and inner diameter values of threaded rods (or drillholes) are 40 and 32 mm, respectively. The diameter and length of steel bars used in the present tests are 10 and 300 mm, respectively. Table 2 summarizes all of the dimension values of the threaded rods used in the laboratory tests.

The drillhole surfaces were created by placing and fixing the smooth and threaded rods at the center of the pullout box. Then soil was placed and compacted in three layers (thickness of each layer was 100 mm) in the pullout box around the threaded rod. After the compaction work of soil in the pullout box, the threaded rod was slowly rotated and pulled out of the box. Therefore, a complete rough drillhole surface was created and used for the following grouting work. Fig. 3 shows the created internal drillhole surfaces after two corresponding threaded rods were removed from the compacted soil in the pullout box. The threaded heights can be clearly observed in the two figures (as marked by white lines). Cement grout was then injected into the drillhole

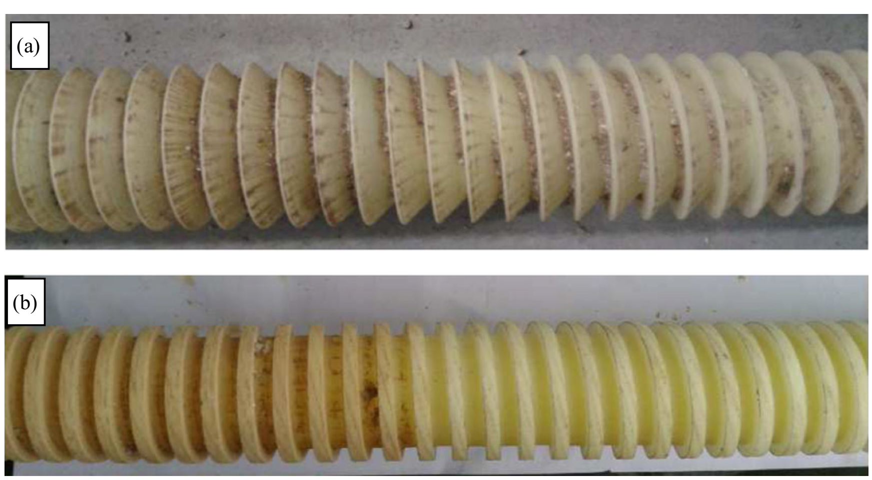

**Fig. 1.** Two cross-sectional shapes of plastic threaded rods for the creation of rough internal drillhole surfaces in a pullout box: (a) triangular shape (Type T surface); (b) rectangular shape (Type R surface)



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under gravity (no pressure). The water–cement ratio of cement grout was 0.42.

### *Laboratory Pullout Test*

Laboratory tests were carried out after 7 days of curing time for the cement grout in the smooth and rough drillholes. The basic pullout

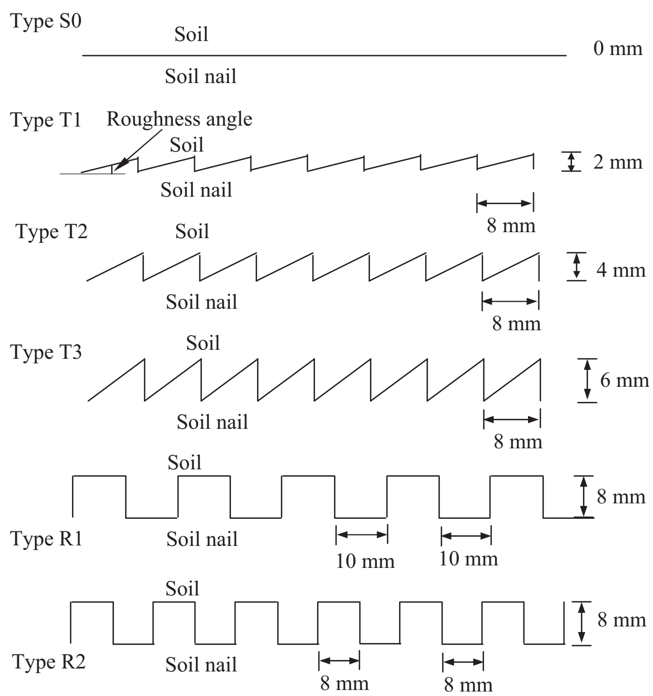


**Fig. 2.** Six types of internal drillhole surface conditions of different model soil nails in pullout tests

test setup is shown in Fig. 4, including a pullout box, loading device at the soil nail head for the application of pullout force, and two transducers for the measurement of pullout displacement of the nail head and mobilized pullout force, respectively. Pullout force was applied step by step and maintained 1 kN for 10 min for each loading step at the soil nail head. After the maximum pullout

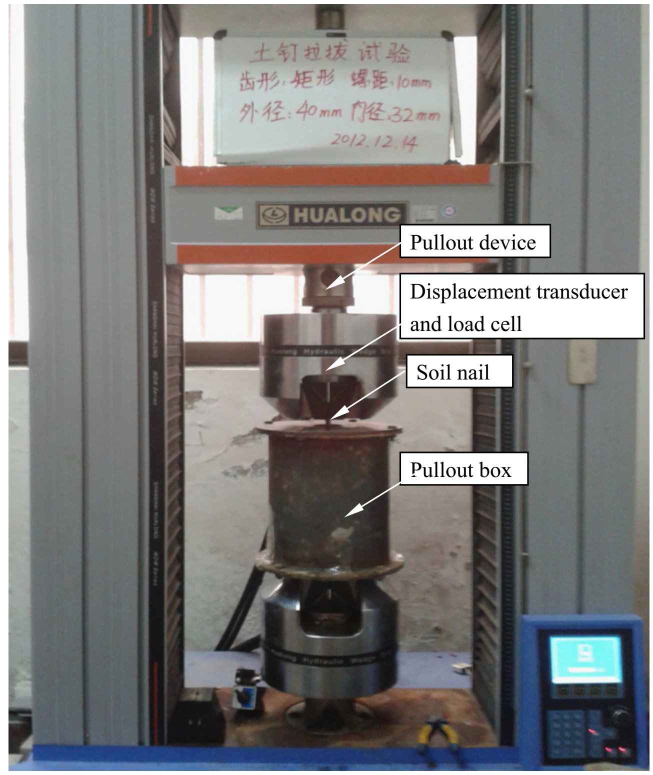


**Fig. 4.** Pullout test setup of a model soil nail in laboratory

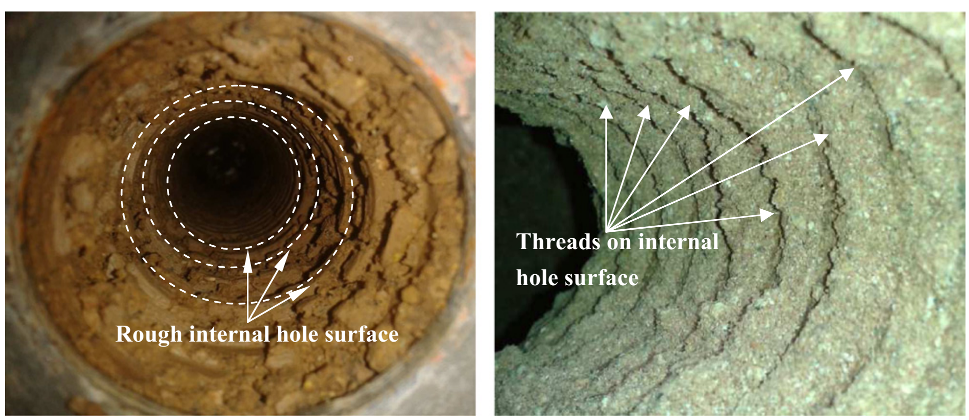


**Fig. 3.** Rough condition of internal drillhole surface before placement of steel bar

**Table 2.** Dimension Values of Different Model Soil Nails in Laboratory Pullout Experiments

| Soil nail types | Cross-sectional shape | Inner bar diameter (mm) | Outer bar diameter (mm) | Nail length (mm) | Steel bar diameter (mm) | Thread height (mm) | Thread spacing (mm) |
|---|---|---|---|---|---|---|---|
| S0 | Smooth | 40 | 40 | 300 | 10 | 0 | 8 |
| T1 | Triangle | 32 | 40 | 300 | 10 | 2 | 8 |
| T2 | Triangle | 32 | 40 | 300 | 10 | 4 | 8 |
| T3 | Triangle | 32 | 40 | 300 | 10 | 6 | 8 |
| R1 | Rectangle | 32 | 40 | 300 | 10 | 8 | 10 |
| R2 | Rectangle | 32 | 40 | 300 | 10 | 8 | 8 |

force was approached in the test, the pullout force was applied continuously at a speed of 1 mm/s. Finally, the model soil nail was completely pulled out of the box for the measurement of water content values and soil nail perimeters at three locations along the soil nail body, including soil nail head, middle, and tip.

The boundary effect of the pullout box is a critical consideration, so that the designed dimensions of the box should at least eliminate the boundary effect on the pullout resistance of the soil nail. The simulation results conducted by Yin et al. (2011) and Yin and Su (2006) show that the vertical stress change is around 5% at a point around 300–400 mm away from hole center before and after excavation. The soil-nail diameter used in this experiment was 100 mm, so that the ratio of affecting distance over drillhole radius is approximately 6 times. The theoretical studies (Yin et al. 2011; Yu 2000) also indicate that the excavation effect up to 5% on the surrounding stress change is approximately 6 times the radius of the drillhole center. This value (6 times) is much closer to the simulation results presented by Yin and Su (2006). The internal diameter and length of the present pullout box are both 400 mm. The ratio of the internal diameter of the pullout box over the diameter of the drillhole (40 mm) is 10 times in the present experiment (i.e., much larger than 6 times), so that the boundary effect on the surrounding stress, and furthermore, the pullout resistance of the soil nail, is limited.

## Experimental Results and Discussion

### *Verification of Present Test Data with the Model Proposed by Luo et al. (2000)*

A total of six pullout tests of model soil nails were carried out in the present laboratory tests taking into account the variations of different roughness conditions of internal drillhole surfaces, including smooth Type S0, Type T (three subtypes, T1, T2, and T3), and Type R (two subtypes, R1 and R2) surfaces (Fig. 2). Fig. 5 illustrates a typical relationship between pullout force of the soil nail head and pullout time in a pullout test. It is seen that the pullout force is applied in a step-by-step form and kept around 10 min for each step. The pullout force drops quickly after achieving the peak value in this test. The pullout shear stress of the soil nails is calculated by dividing the pullout force values with the contact area between soil and soil nail as shown below:

$$\tau = \frac{P}{\pi DL} \tag{1}$$

where $P =$ pullout force values; and $D$ and $L =$ measured average diameter and length of the soil nail after it has been completely pulled out.

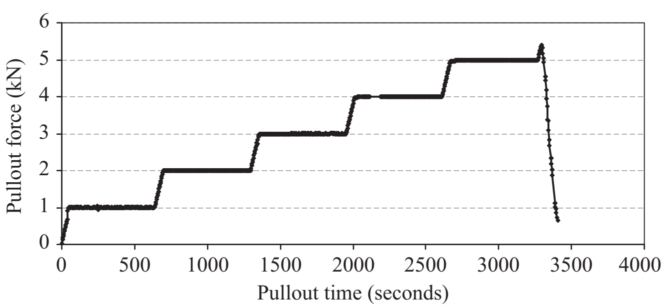


**Fig. 5.** Typical relationship between pullout force and pullout time of a model soil nail

For cement-grouted soil nails, the drilling process in the present test released all overburdened soil pressure so that only slight postinstallation normal stress remained surrounding the soil nail after grouting (Yin et al. 2011). During the pullout process, both the postinstallation normal stress $\sigma'_m$ and the normal stress $\Delta\sigma'_m$ resulting from soil dilation are assumed to distribute uniformly around the soil nail. Therefore, the total average normal stress around the soil nail can be calculated using $q'_{\max} = \sigma'_m + \Delta\sigma'_m$. The postinstallation normal stress is assumed to be 5 kPa for the present test, and an additional normal stress due to soil dilation is calculated using the following equation:

$$\Delta\sigma'_m = \frac{Gu_c}{r_0}\tan\psi'_{\max} \tag{2}$$

The total average normal stress acting on the soil nail can be given according to Eq. (2):

$$q'_{\max} = \sigma'_m + \Delta\sigma'_m = \sigma'_m + \frac{Gu_c}{r_0}\tan\psi'_{\max} \tag{3}$$

where $\psi'_{\max}$ and $r_0 =$ maximum dilation angle and radius of the soil nail, respectively. The critical shear displacement, shear modulus, and maximum dilation angle are 2 mm, 10 GPa, and 15°, respectively. Luo et al. (2000) described the soil nail as teeth sliding along the failure surface owing to relatively high stiffness compared with the surrounding soil. The measured friction angle of the failure surface $\phi'_f$ may involve two components, i.e., angle of friction between soil particles and microfacets ($\delta'_f$), as well as the inclination angle of microfacets ($i'_f$):

$$\phi'_f = \delta'_f + i'_f \tag{4}$$

The present experimental observation indicates that the true failure surfaces partially present at the initial drillhole surface with inclined microfacets (thread surfaces). It is assumed that the contributed proportion of inclination angle of microfacets (thread surfaces) to the true friction angle is $m$ ($0 \le m \le 1$). Therefore, the true friction angle of the failure surface in Eq. (4) may be rewritten as

$$\phi'_f = \delta'_f + mi'_f \tag{5}$$

The maximum shear stress of failure surface for dilative soil can be calculated using the analytical model developed by Luo et al. (2000):

$$\tau_{\max} = q'_{\max}\tan\phi' = \left(\sigma'_m + \frac{Gu_c}{r_0}\tan\psi'_{\max}\right)\tan\phi'_f = \left(\sigma'_m + \frac{Gu_c}{r_0}\tan\psi'_{\max}\right)\tan(\delta'_f + mi'_f) \tag{6}$$

Eq. (6) can be used to calculate the maximum shear stress of the interface between the soil and soil nail. Table 3 summarizes all parameter values adopted in the comparison study between the present measured test data and calculated results from the analytical model by Luo et al. (2000). Fig. 6 shows the comparison between test data and model results from Luo et al. (2000). It is clear that both series of data agree fairly well and increase almost linearly with the increase in the roughness angle.

### *Relationships between Pullout Resistance and Pullout Displacement*

Variations of pullout resistance (pullout force and shear stress of interaction interface between soil and cement grout) against pullout displacement of soil nail heads are summarized and illustrated in Figs. 7(a–d). The pullout force results in Figs. 7 (a and c) are directly measured at the soil nail head, but the values of interface shear stress in Figs. 7(b and d) are the results calculated by dividing the pullout force with the surface area of the model soil nails after they have been completely pulled out of the ground using Eq. (1). It is noted that the surface area used for the calculation of shear stress is the multiplication between the average external perimeter and length of the pulled-out soil nail.

It is seen from Figs. 7(a–d) that all pullout resistance variations against displacement relationships show obvious peak and postpeak behavior for different types of model soil nails. That is, relationships of pullout resistance with respect to pullout displacement show obvious softening behavior. The peak pullout resistance of the model soil nail (marked by circles in all four figures) grouted in the smooth drillhole surface is the smallest among all measured results. The rougher the internal drillhole surface, the larger the peak pullout resistance or the higher the peak shear stress of the interface at specific pullout displacement level. Figs. 8(a and b), respectively, shows the R-type soil nail and the T-type soil nail after they have been completely pulled out of the pullout box in the laboratory for visual examination. The triangular and rectangular shapes of the cross sections can be clearly observed in both photos.

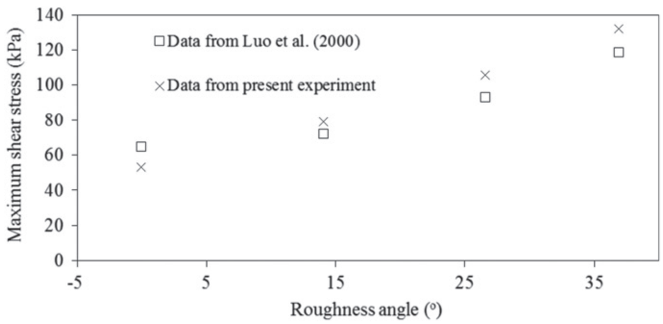


**Fig. 6.** Comparison between measured results and model results from Luo et al. (2000)

To improve the understanding of pullout resistance associated with the roughness conditions of drillhole surface, all peak values of pullout resistance at different roughness angles are summarized and compared with Figs. 9(a and b). Roughness angle in the two figures is calculated using the thread height and spacing as marked in Fig. 2. It is clear that all peak values of pullout resistance (both pullout force and shear stress of interface) against roughness angle relationships can be fitted using pure linear relationships. The increase of roughness angle leads to a related rise of pullout resistance of soil nails and therefore improves the safety condition of reinforced structures. All obtained pullout resistance values can be approximated as linear relationships with respect to roughness angle at a specific pullout displacement.

In real applications, the core drill bit may create relatively smooth internal drillhole soil nail surfaces, for example, the smooth drillhole surface created by using core drill bits in the laboratory (Chu and Yin 2005; Su et al. 2008; Yin and Su 2006).

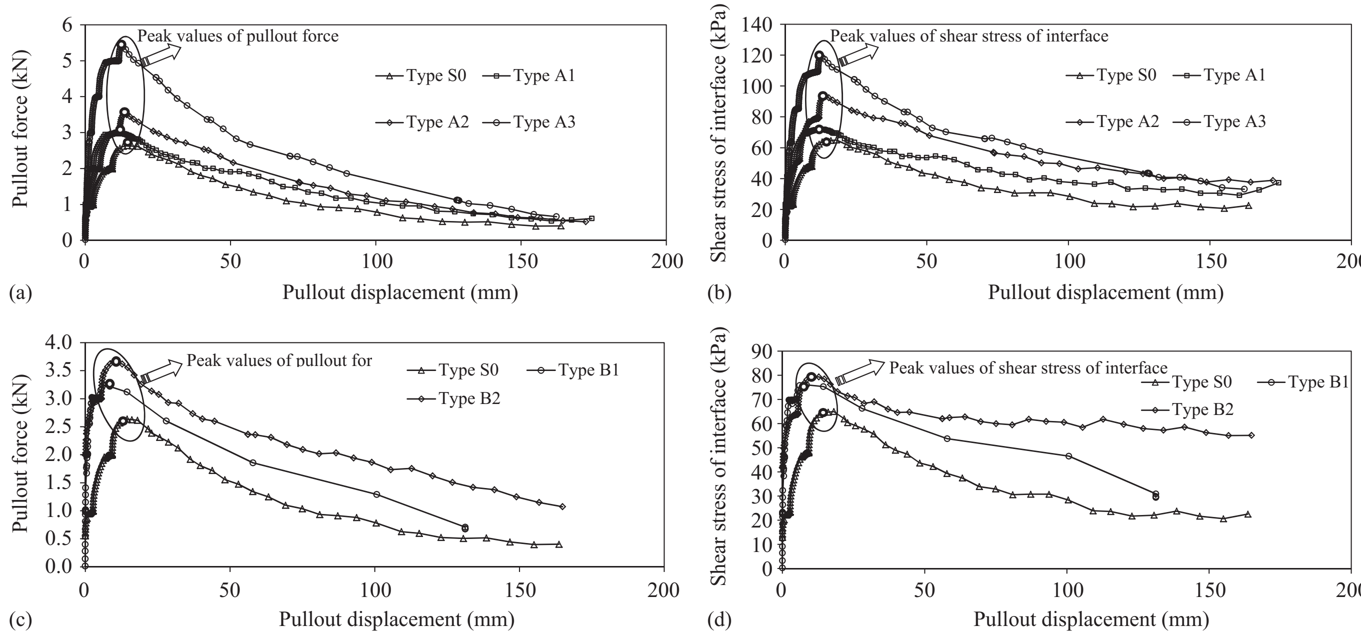


**Fig. 7.** Relationships of pullout resistance against pullout displacement of Types A and B model soil nails: (a) pullout force versus pullout displacement for Type A soil nail; (b) shear stress of interface versus pullout displacement for Type A soil nail; (c) pullout force versus pullout displacement for Type B soil nail; (d) shear stress of interface versus pullout displacement for Type B soil nail

**Table 3.** Parameter Values Adopted in Comparison Study between Test Data and Model Data

| Soil nail type | $i_f'$ (degrees) | $\psi'_{\max}$ (kPa) | $\delta_f'$ (degrees) | $m$ | $\phi_f'$ (degrees) | $G$ (MPa) | $u_c$ (mm) | $\sigma'_m$ (kPa) | $r_0$ (m) |
|---|---|---|---|---|---|---|---|---|---|
| S0 | 0 | 15 | 20 | 0.6 | 20 | 8 | 2 | 5 | 0.02 |
| T1 | 14.0 | 15 | 20 | 0.6 | 28.421746 | 8 | 2 | 5 | 0.02 |
| T2 | 26.6 | 15 | 20 | 0.6 | 35.939031 | 8 | 2 | 5 | 0.02 |
| T3 | 36.9 | 15 | 20 | 0.6 | 42.121939 | 8 | 2 | 5 | 0.02 |

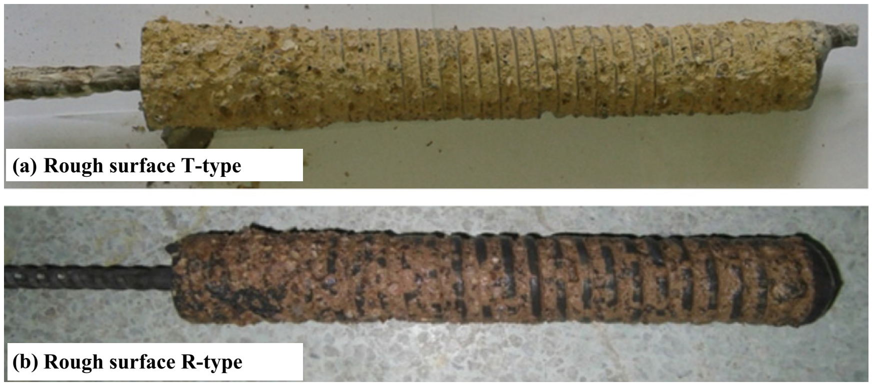


**Fig. 8.** (a) Soil nail of T-type rough surface; (b) soil nail of R-type rough surface after it has been completely pulled out of the ground

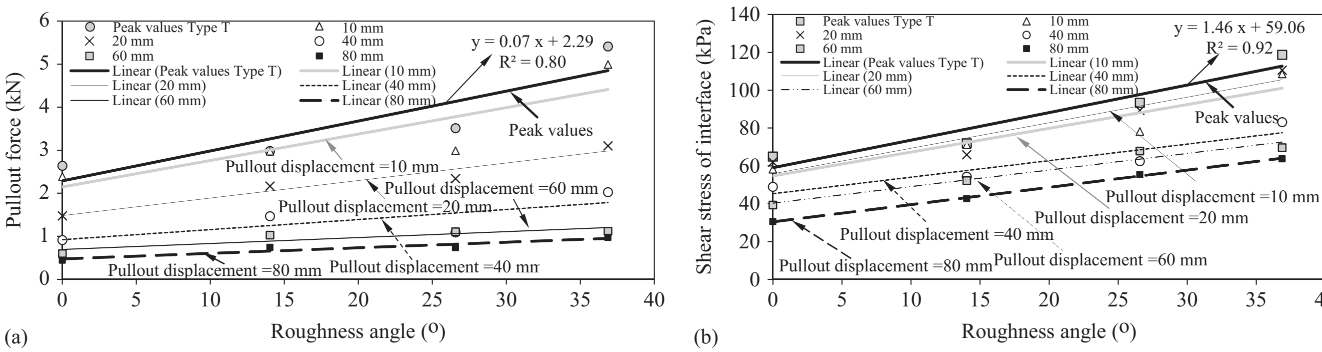


**Fig. 9.** Pullout resistance values of different model soil nails against roughness angle values for Type T soil nails: (a) pullout force against roughness angle values; (b) shear stress of interface against roughness angle values

The internal drillhole surface seems to be very smooth, at least from observations of laboratory photos. The obtained test results in these laboratory tests may underestimate the real pullout resistance significantly. However, the sacrificial drill bit, which is commonly adopted by field engineers, normally creates relatively rough drillhole surfaces as the rotational cutting elements on the drill bit continuously damage the soil in drillholes. This process may result in irregular and rough drillhole surfaces, which lead to a substantial increase in frictional resistance compared with the soil nail with smooth surface in laboratory pullout tests.

### *Pullout Resistance at Different Pullout Displacement of Soil Nail Heads*

Figs. 10(a–c) show, respectively, the measured pullout force of Type T soil nail, calculated shear stress of interface of Type T soil nail, and calculated shear stress of interface of Type R soil nail at different pullout displacements of nail head. The calculated results of shear stress of the interface for Type T and Type R drillhole surfaces of soil nails are obtained using Eq. (1). It is clear that the pullout force as well as the shear stress values decrease linearly with an increase in pullout displacement. The maximum reduction was around 2.0 kN for Type T3 soil nail (from 3.0 to 1.0 kN) and a lowest reduction of 1.7 from 2.5 to 0.8 kN for Type S0 soil nail. Pullout force values of the soil nail with the maximum roughness angle (Type T3) and smooth drillhole surface (Type S0) are the largest and lowest, respectively, among all measured results.

Calculated shear stress values of interface decrease almost linearly as the increase of pullout displacement of the nail head as shown in Fig. 10(b), similar to the measured pullout force variations of soil nails grouted in the Type T drillhole surface in Fig. 10(a). The rougher the drillhole surface, the higher the mobilized peak shear stress of the interface; however, the pullout displacement values vary substantially. The maximum reduction of shear stress values for rough soil nails (Type T3) is almost twice the magnitude of the results of soil nails with smooth drillhole surface (from 110 to 65 kPa for Type T3 soil nails and from 60 to 30 kPa for Type S0 soil nails). Similarly, it is clear in Fig. 10(c) that the increase of thread density (from Type S0 to Type R1 and Type R2) or the decrease of thread spacing leads to a corresponding rise of mobilized shear stress of the interface between soil and soil nail. In addition, the increase of pullout displacement results in a related linear reduction of the shear stress of the interface.

### *Proportions of Pullout Resistance Increase for Soil Nails Grouted in Rough Drillholes*

Quantification of the effect of roughness conditions on the pullout resistance of soil nails is critical for a comprehensive understanding of the complicated interaction process between soil and soil nail. The calculation of the proportion of pullout resistance increase for different roughness conditions of internal drillhole surface $\eta$ is calculated using the following relationship:

$$\eta = \frac{P_r - P_s}{P_s} \times 100\% \tag{7}$$

where $P_r$ and $P_s$ = pullout force values for soil nails with rough drillhole surface and smooth surface, respectively. Figs. 11(a and b) show the proportions of pullout resistance increase with pullout displacement for soil nails with Type T drillhole surface (Types

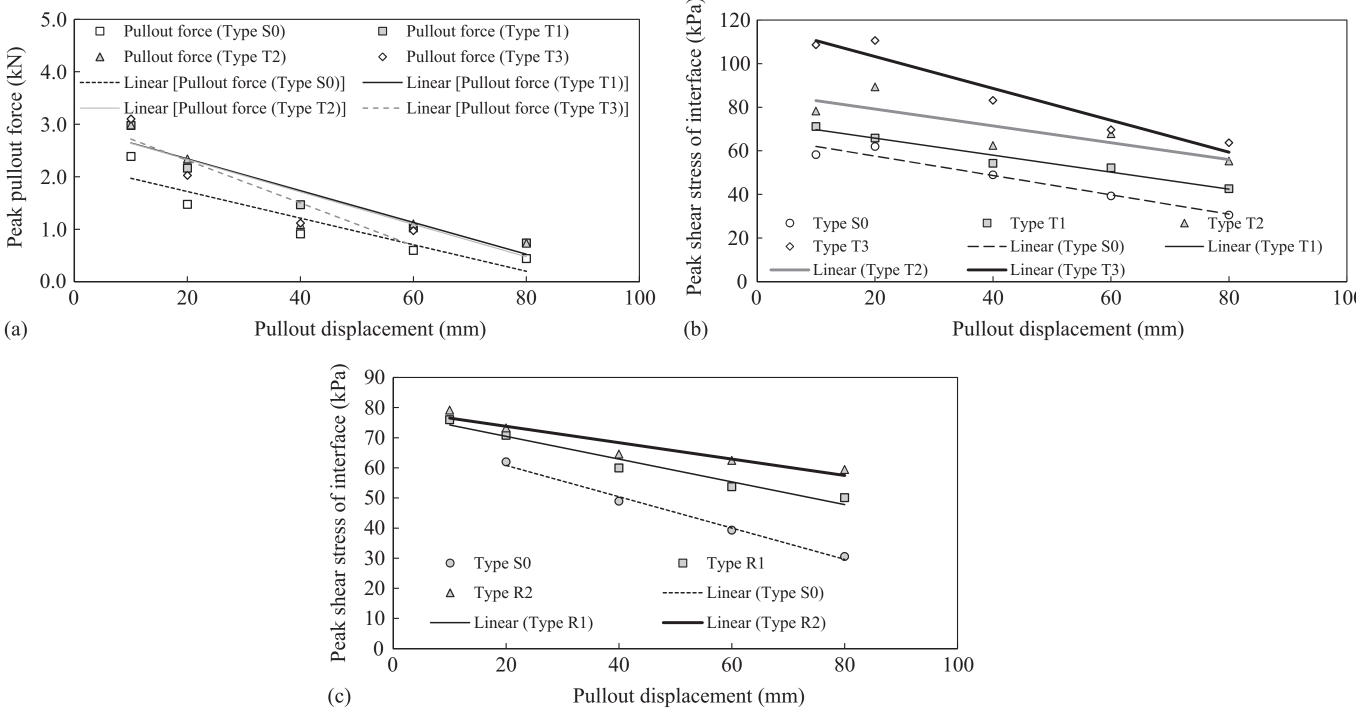


**Fig. 10.** Relationships between pullout resistance and pullout displacement: (a) peak pullout force against pullout displacement for smooth and Type T soil nails; (b) peak shear stress of interface against pullout displacement for smooth and Type T soil nails; (c) peak shear stress of interface against pullout displacement for smooth and Type R soil nails

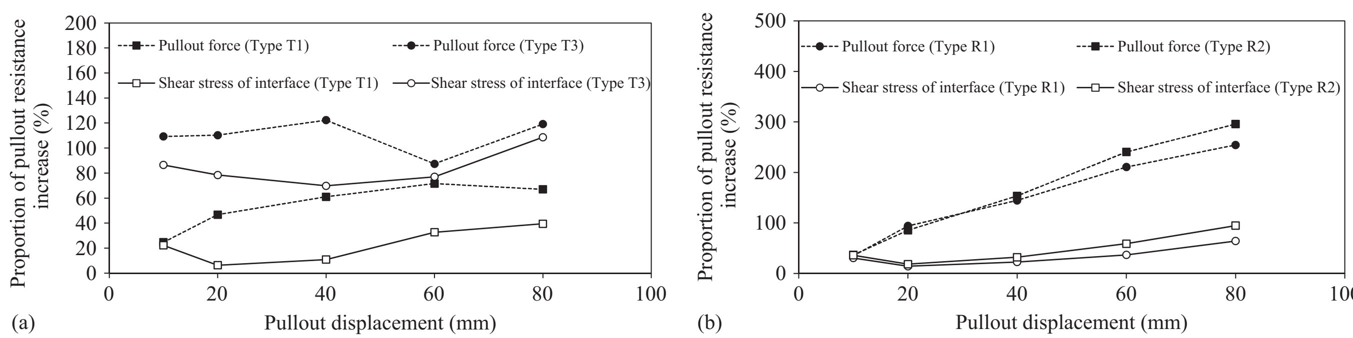


**Fig. 11.** Variations of proportion of pullout resistance increase against pullout displacement for soil nails with (a) Type T drillhole surface; and (b) Type R drillhole surface

T1 and T3) and with Type R drillhole surface (Types R1 and R2), respectively. It is seen from Fig. 11(a) that the increased proportions for Type T3 soil nails are mostly higher than 80 and 60% in pullout force and peak shear stress of the interface, respectively. The maximum increased proportion of pullout resistance approaches approximately 140% for the pullout force of T3 soil nails. This indicates that the rough drillhole surface enhances the pullout resistance (both the peak shear stress and pullout force) of soil nails significantly. However, for the soil nail with relatively less rough drillhole surface, for example, the Type T1 soil nail, the increased proportions of both pullout force and peak shear stress of the interface reduce almost 70% on average compared with the Type T3 soil nail, with the lowest increased proportion of shear stress of around only 5%. For the pullout test results of Type R drillhole surface, as shown in Fig. 11(b), the increased proportions of pullout force and peak shear stress of the interface between soil and soil nail [calculated using Eq. (7)] show a continuous rise with the increase in pullout displacement. This increasing trend appears to be more obvious for pullout force results than for the peak shear stress of the interface.

Fig. 12 shows the relationships between the proportions of peak pullout-resistance increase for different soil nails. For soil nails with Type T drillhole surface, peak pullout resistance shows a continuous rise, and the maximum increased proportion approaches 110% (Type T3 soil nail) compared with the soil nail with the smooth drillhole surface (Type S0, as marked in Fig. 11). The observed test results of soil nails with Type R drillhole surface present variation trends similar to the Type T soil nail, with a maximum increased proportion of approximately only 40%. These increased proportions of pullout resistance increments indicate that the peak pullout resistance of soil nails can be effectively enhanced by using the triangular cross-sectional shapes of soil nail surfaces. The decrease of thread spacing (no variation in thread height) leads to a corresponding increase of pullout resistance. However, this conclusion may not be always hold; when the spacing reduces significantly, the surface of internal drillhole could

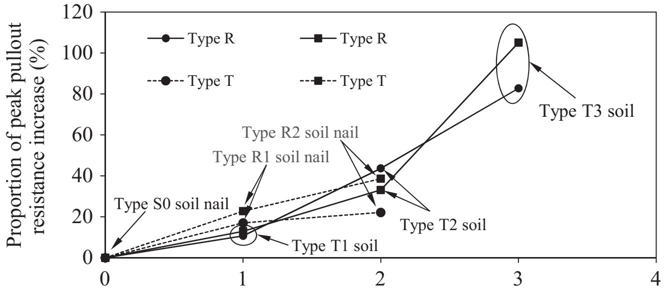


**Fig. 12.** Proportions of pullout resistance increase against roughness of drillhole surface for different model soil nails

**Table 4.** Measured Parameter Results of Different Model Soil Nails in Pullout Tests

| Soil nail types | Measured perimeter (mm) Soil nail head | Middle location | Soil nail tip | Average perimeter |
|---|---|---|---|---|
| S0 | 185 | 146 | 130 | 154 |
| T1 | 137 | 165 | 162 | 155 |
| T2 | 169 | 136 | 152 | 152 |
| T3 | 199 | 165 | 149 | 171 |
| R1 | 170 | 156 | 149 | 158 |
| R2 | 177 | 165 | 174 | 172 |

Note: Measured perimeter is the external perimeter after a model soil nail was completely pulled out of the ground.

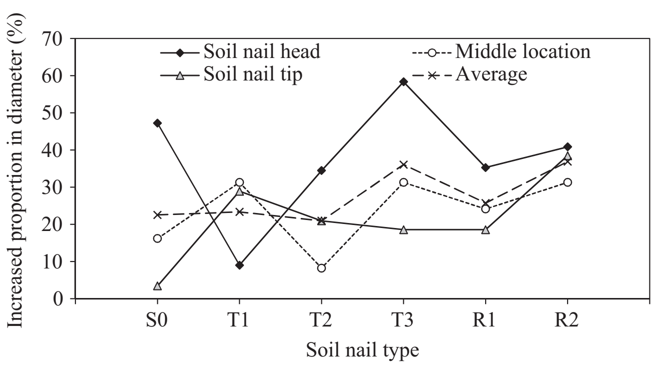


**Fig. 13.** Proportions of external diameter increase for different soil nails

be approximated as a smooth surface, which would reduce the pullout resistance significantly.

Detailed information regarding the perimeter values of pulled-out soil nails with rectangular and triangular thread shapes is summarized in Table 4. The drillhole perimeter can be calculated as below:

$$L = \pi D = 3.14 \times 40 = 125.6\ \text{mm} \tag{8}$$

where $L$ and $D =$ perimeter and diameter of the grouted soil nail, respectively. From the measurement results shown in Table 4, it can be seen that most soil nails have expanded significantly in the diametrical direction of the model soil nails. To clearly quantify the expanded effect of these pulled-out soil nails, the diameter-increased proportion is taken into account and calculated using the below formula:

$$\beta = \frac{D_0 - D_F}{D_0} \times 100\% \tag{9}$$

where $D_0$ and $D_F =$ drillhole diameter and the average diameter of the pulled soil nail in the present tests. Fig. 13 summarizes all increased proportion $\beta$values against soil nail types. It is seen most soil nail diameters, after they have been pulled out of the ground, increase by approximately 10–30% compared with their original drillhole diameter. The maximum increase of diameter approaches 60% (Type T3), indicating that the rough soil nail creates a thick soil layer that adheres to the soil nail surface after it is pulled out. The failure surface due to pullout force presents at a certain distance away from the original drillhole surface, leading to a larger pulled-out diameter of soil nail and a farther distance of failure surface away from original drillhole surface.

## Summary and Conclusions

A number of pullout tests were carried out focusing on the effect of two typical drillhole roughness conditions on the pullout resistance of model soil nails. The two typical roughness conditions were created using a simple and effective method to create different cross-sectional shapes of threads on an internal drillhole surface. From systematic pullout tests of models soil nails and related experimental measurements and observations, the main conclusions are summarized as follows:

1. Both the peak pullout resistance values and the pullout resistance values at specific pullout displacement levels for T-type soil nails are found to increase approximately linearly with the increase of roughness angle (from 0 to 37°). The pullout resistance value of R-type soil nails decreases almost linearly with the increase of pullout displacement.
2. The Type T soil nail is found to be effective in increasing the mobilized pullout resistance of model soil nails. The peak pullout force and related shear stress of the interface are found to increase significantly compared with the results of the smooth soil nail, with maximum increments of 120% in shear stress of the interface and approximately 110% in pullout force.
3. The soil nail with Type R surface is efficient in the mobilization of the pullout resistance of soil nails. Pullout force and shear stress of interface results at specific pullout displacements for the Type R soil nail are found to increase approximately 300 and 280%, respectively, compared with the pullout resistance results of the smooth soil nail.
4. Soil nail diameter values are found to expand significantly compared with the drillhole diameter values in all pullout tests. The maximum increased proportion of soil nail diameter approaches 60%, and the most-increased proportions are approximately 10–30% compared with the original diameter of the drillholes.

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