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Evaluations of load-deformation behavior of soil nail using hyperbolic pullout model

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Abstract. Soil nailing, as an effective stabilizing method for slopes and excavations, has been widely used worldwide. However, the interaction mechanism of a soil nail and the surrounding soil and its influential factors are not well understood. A pullout model using a hyperbolic shear stress-shear strain relationship is proposed to describe the load-deformation behavior of a cement grouted soil nail. Numerical analysis has been conducted to solve the governing equation and the distribution of tensile force along the nail length is investigated through a parametric study. The simulation results are highly consistent with laboratory soil nail pullout test results in the literature, indicating that the proposed model is efficient and accurate. Furthermore, the effects of key parameters, including normal stress, degree of saturation of soil, and surface roughness of soil nail, on the model parameters are studied in detail.

Keywords: soil nail; hyperbolic stress-strain relationship; pullout test; interface shear resistance

1. Introduction

Landslides, debris flows and other slope related geo-hazards occur frequently in hilly or mountainous regions, which induce considerable economic loss and fatal damages annually. Since 1970s, soil nailing has been certified to be an effective and reliable supporting method, and has been widely utilized to stabilize slopes or other geo-structures all over the world. The cement grouted soil nail, as the most common soil nail in engineering practice, is composed of a ribbed steel bar embedded in a borehole and grouted by gravity or under low pressure. In working condition, the shear stresses are mobilized at the soil-grout interface in the opposite direction toward the critical slip surface to resist soil deformation and in consequence the slope stability is improved (Zhu *et al*. 2012).

The pullout resistance of soil nail is found to be influenced by a number of factors, such as

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construction conditions, properties of soil, grouting methods, roughness of soil-grout interface, and geometry of slope and drillhole (e.g., Milligan and Tei 1998, Luo *et al*. 2000, Hong *et al*. 2003, Su *et al*. 2008, Yin *et al*. 2009, Yin and Zhou 2009, Seo *et al*. 2012). A review of the literature indicates that, among all the affecting factors, the overburden pressure and the grouting pressure are especially studied and discussed. Pradhan *et al*. (2006) studied the pullout interaction of grouted soil nails in loose fill materials and a numerical model based on the spring-bar model was used to analyze the test results. Su *et al*. (2007) studied the influence of degree of saturation on the shear resistance. The test results show that the pullout shear resistance peaked at degrees of saturation between 50% and 75%. Yin *et al*. (2009) performed a series of laboratory soil nail pullout tests, and found that the average peak shear stress of soil-grout interface varies linearly with the grouting pressure from 0 kPa to 130 kPa. A further study carried out by Yin and Zhou (2009) shows that the influences of normal stress and grouting pressure on the soil nail pullout resistance are interactional. In the above studies, the shear stress of soil-grout interface is commonly assumed to be uniformly distributed along the nail length and the deformation behavior of soil nail under pullout loading is not well addressed in detail.

In this paper, a pullout model based on hyperbolic stress-strain relationship is proposed to describe the load-deformation behavior of a soil nail. The distribution pattern of tensile force under different model parameters is explored using a parametric study. The proposed pullout model is then verified through a comparison between the numerical simulation results and laboratory pullout test data from Chu and Yin (2005a, b). The influences of some factors, including normal stress, degree of saturation of soil, and surface roughness of soil nail, on shear resistance and shear coefficient of the soil-grout interface, are further analyzed and discussed.

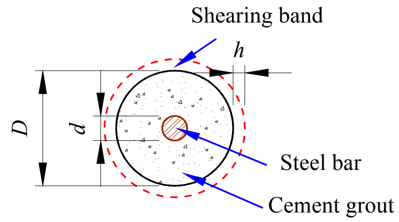
2. Hyperbolic soil nail pullout model

2.1 Interaction mechanism at soil-grout interface

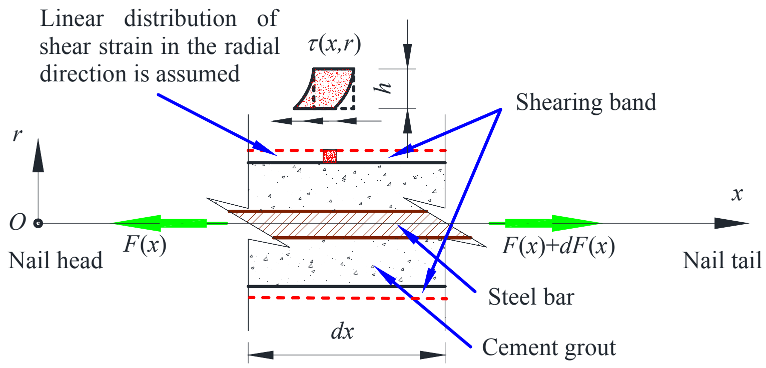
A mechanical model of the pullout of a soil nail is shown in Fig. 1. In this two-dimensional cylindrical coordinate system, the soil nail is considered as an axial tension member in the x direction while radial deformation in the r direction is neglected. When subjected to pullout loading, shear stresses are mobilized at the soil-grout interface to resist the pullout force. It should be noted that only a thin layer of soil at the soil-grout interface (i.e., shearing band) is subjected to shearing. To keep the analysis simple, the thickness of this shearing band is assumed to be uniformly distributed along the nail length. Thus the axial displacement $u_s(x, r)$ of the soil in contact with the soil nail can be regarded as equal to that of the soil nail $u(x)$ before slippage or debonding of the soil-gout interface occurs (Milligan and Tei 1998), i.e.

$$u(x) = u_{\mathrm{s}}(x,r)_{r=D/2} = -\int_{D/2}^{D/2+h} \gamma_s(x,r)\mathrm{d}r \tag{1}$$

in which x = distance from the nail head; r = distance from the center of cross section in the radial direction; D = diameter of the grouted soil nail; h = thickness of the shearing band; and $\gamma_s(x, r)$ = shear strain within the soil mass. In the study of Zhu *et al*. (2011), the shear strain of the shearing band is assumed to be constant in the radial direction. Because the shear strain reduces to zero suddenly at the outer boundary of the shearing band, the deformation compatibility of soil mass



(a) Sectional view



(b) Side view

Fig. 1 Schematic illustration of pullout mechanism of a soil nail

cannot be satisfied. Here we employed the assumption that the shear strain decreases linearly in the radial direction, as suggested by Milligan and Tei (1998). Therefore, the nail displacement can be expressed by

$$u(x) = -\gamma_s(x,r)_{r=D/2}\int_{D/2}^{D/2+h}\left(\frac{\frac{D}{2}+h-r}{h}\right)\mathrm{d}r = -\frac{h}{2}\gamma_s(x,r)_{r=D/2},\quad \frac{D}{2}\le r\le\frac{D}{2}+h \tag{2}$$

In order to describe the shear stress-strain relationship at the soil-grout interface, the widely used hyperbolic model shown in Fig. 2 is adopted (Kondner 1963, Hirayama 1990, Milligan and Tei 1998, Gomez *et al*. 2003). The relationship between shear stress $\tau(x)$ and shear strain $\gamma(x)$ can be expressed by

$$\tau(x) = \frac{\gamma(x)}{\frac{1}{G_0}+\frac{1}{\tau_{\mathrm{ult}}}\gamma(x)} \tag{3}$$

where τ_{ult} = ultimate asymptotic value of shear stress (i.e., interface shear resistance); G_0 = initial shear modulus. Taking $G_0^* = 2G_0/h$ as the shear coefficient at the soil-grout interface and noting that $\gamma_s(x, r)_{r=D/2} = \gamma(x)$, the relationship between the interface shear stress and nail displacement is

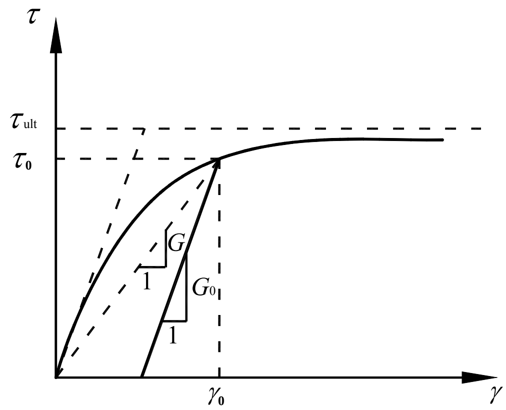


Fig. 2 Hyperbolic shear stress-shear strain relationship of soil-grout interface (Zhu *et al*. 2011)

then given as

$$\tau(x) = \frac{u(x)}{-\frac{1}{G_0^*} + \frac{1}{\tau_{ult}} u(x)} \tag{4}$$

2.2 Formulation of the soil nail pullout model

As the soil nail is considered as an axial tension member, the longitudinal equilibrium of the nail element gives (Zhu *et al*. 2011)

$$F(x) = \frac{\pi}{4} D^2 \overline{E} \varepsilon(x) = \frac{\pi}{4} D^2 \overline{E} \frac{du(x)}{dx} \tag{5}$$

in which $F(x)$ = tensile force in the soil nail; $\varepsilon(x)$ = uniaxial strain in the soil nail; $\overline{E}$ = weighted average Young's modulus of the soil nail. In this equation, an axial force is considered positive (negative) for tension (compression).

Besides, in the mechanical model mentioned above, the resistance of the soil nail against the pullout force is provided by the shear stress acting on the soil-grout interface. Hence the following differential equation can be derived from the equilibrium of a uniaxial soil nail element (Sawicki 1998)

$$\frac{dF(x)}{dx} = -\pi D \tau(x) \tag{6}$$

Eqs. (4)-(6) lead to the following governing equation

$$\frac{d^2F}{dx^2} = \frac{4G_0^* F}{\pi^2 \overline{E} D^3 \tau_{ult}^2} \left(\frac{dF}{dx} + \pi D \tau_{ult} \right)^2 \tag{7}$$

Eq. (7) may also be converted to a normalized form by defining the normalized tensile force F' and the normalized distance x', i.e.

$$\begin{cases} F' = F / F_0 \\ x' = x / L \end{cases} \tag{8}$$

in which F_0 = pullout force applied on the nail head; and L = length of the soil nail. Then we get

$$\frac{\mathrm{d}^2 F'}{\mathrm{d}x'^2} = \alpha \left(\beta \frac{\mathrm{d}F'}{\mathrm{d}x'} + 1 \right)^2 F' \tag{9}$$

where

$$\alpha = \frac{4 G_0^* L^2}{\bar{E} D} \tag{10}$$

$$\beta = \frac{F_0}{\pi D L \tau_{ult}} \tag{11}$$

It is clear that α and β are two dimensionless parameters. The former is related to the dimensions of the soil nail and the relative stiffness of the nail to the surrounding soil. The latter lies in the range of 0~1. Eq. (9) is a second-order differential equation and may be solved with specified boundary conditions. In a standard soil nail pullout test, the pullout force F_0 is measured by a load cell or determined from the pressure gauge reading of the hydraulic jack. The tensile force at the nail tail can be neglected. Thus we get the following boundary conditions

$$\begin{cases} F(x = 0) = F_0 \\ F(x = L) = 0 \end{cases} \tag{12}$$

or

$$\begin{cases} F'(x' = 0) = 1 \\ F'(x' = 1) = 0 \end{cases} \tag{13}$$

Therefore, the normalized tensile force F' can be calculated numerically. The corresponding tensile force $F(x)$, interface shear stress $\tau(x)$, and displacement $u(x)$ can then be obtained using Eqs. (8), (6) and (4), respectively. Meanwhile, the relationship between pullout force F_0 and displacement of nail head (pullout displacement) u_0 can be determined. The displacement of nail tail and the extension of soil nail can also be derived.

2.3 Determination of model parameters

The proposed hyperbolic pullout model of soil nail has five parameters: nail length L; nail diameter D; average Young' modulus of the soil nail $\bar{E}$; shear resistance at the soil-grout interface τ_{ult}; and shear coefficient at the soil-grout interface G_0^*. The first two parameters are predetermined by design requirements. The average Young' modulus is dependent on the dimensions and properties of the steel bar and cement grout. The interface shear resistance τ_{ult} and shear coefficient G_0^* can be determined by fitting the experimental curve of pullout force F_0 against displacement of nail head u_0 (Sawicki 1998).

Taking F_{max} as the maximum pullout force obtained in the pullout test procedures, $\beta_{max} = F_{max} / \pi DL\tau_{ult}$. Because debonding at the soil-grout interface will occur before the soil nail is completely pulled out ($u(x) = \infty$), the critical condition where $\beta_{max} = 1$ cannot be reached in engineering practice.

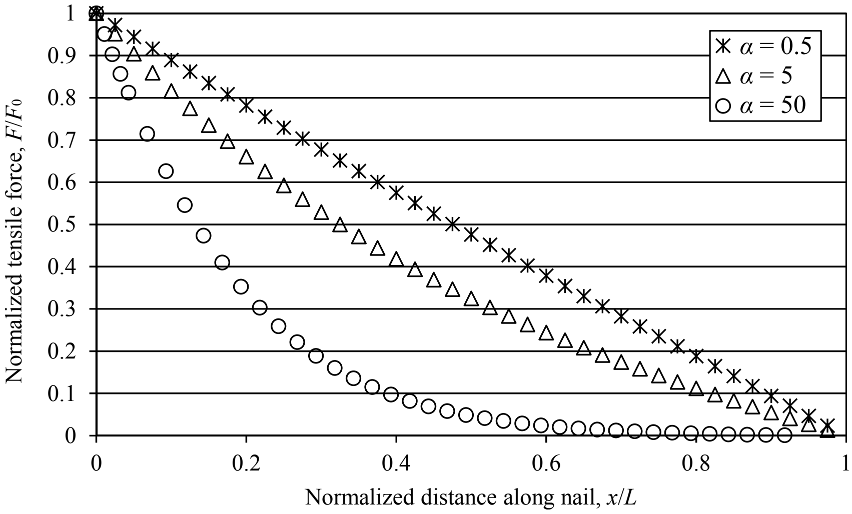
2.4 Distribution pattern of tensile force

Eq. (9) illustrates that the distribution pattern of normalized tensile force is dependent on the two dimensionless parameters α and β. As shown in Fig. 3(a), the normalized tensile forces are approximately linearly distributed with a low α value. With the increase of α, the distributions of normalized tensile force become highly nonlinear, and much of the normalized tensile force is generated in the vicinity of the nail head ($x' = 0$). On the contrary, a small β value results in a nonlinear distribution of normalized tensile force. A large β value will lead to a linear distribution of normalized tensile force. As the interface shear stress is proportional to $dF(x) / dx$, it is thus not rigorous to always assume a uniform distribution of shear stress along the nail length in soil nail analysis. This finding may provide a reference for designing of a soil nail system, and allows us to roughly estimate the distribution of normalized tensile force by $F(x) = (1 - x/L) F_0$ with relatively small α and large β values.

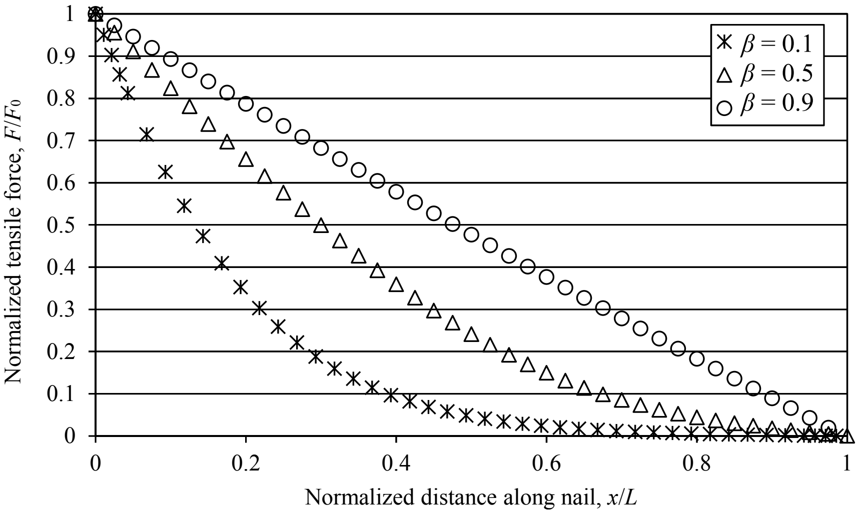
3. Analysis of soil nail pullout test results

3.1 Laboratory pullout tests of cement grouted soil nails

In order to investigate some factors affecting the shear resistance of soil nails, Chu and Yin (2005a, b) conducted a series of laboratory pullout tests. In their tests, the completely decomposed granite (CDG) soil was compacted in six layers in a pullout box to achieve a degree of compaction of 95%. A 100-mm-diameter hole was then predrilled into the compacted soil using a rotary cutting tool with diamond bits. Afterwards, the 32-mm-diameter ribbed steel bar was inserted centrally in the drillhole and a cement mortar with a water-cement ratio of 0.45 was continuously grouted over the drillhole by gravity flow. After curing for about 28 days, the cement grouted soil nail was pulled out using a hydraulic jack. The overburden pressure was applied to the testing soil by water pressure through the rubber diaphragm under the top cover. Two linear variable displacement transformers (LVDTs) were used to measure the pullout displacements at the nail head. In their study, some factors affecting the pullout performance of soil nail were studied through a series of tests: 1) The normal stress varied from 55 kPa to 305 kPa to study the effect of normal stress on the pullout resistance of cement grouted soil nails; 2) The degree of saturation of the CDG soil varied from 70% to 86% to investigate how the soil properties affect the pullout resistance; 3) Pullout tests were conducted on two types of soil nails, i.e. regular surface nails and irregular surface nails, to study the influence of the surface roughness of the soil nail. The soil nails with irregular surface at the soil-grout interface was made by use of a diamond steel plate, which scratched the drillhole surface before grouting. Apart from that, they also performed large size direct shear tests on CDG soil to make a comparison with the pullout tests. For the CDG soil in a natural wet condition (with a degree of saturation of 70%), the shear strength parameters are found to be $c_{DS}' = 45.77$ kPa and $\phi_{DS}' = 30.43°$. Details about their test methods can be found in Chu and Yin (2005a, b).



(a) Influence of α (β = 0.1)



(b) Influence of β (α = 50)

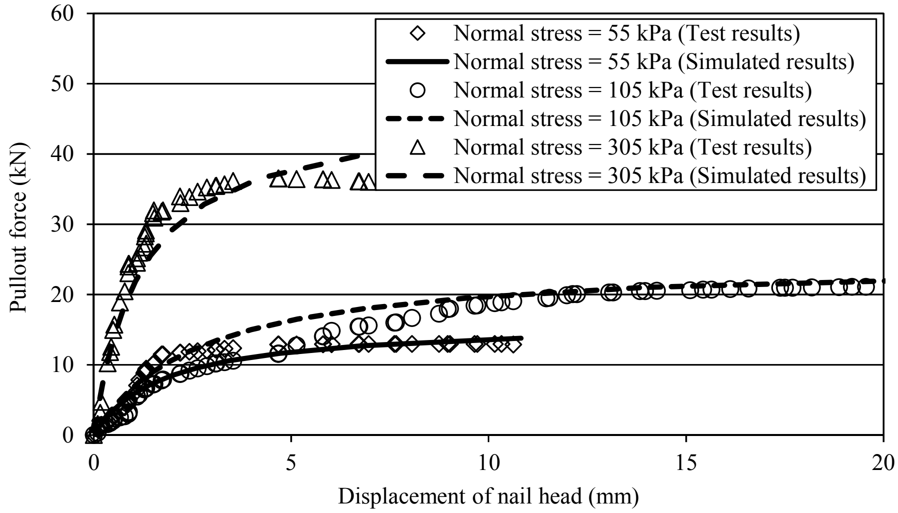
Fig. 3 Distributions of normalized tensile force for different values of model parameters

3.2 Fitting results using the proposed pullout model

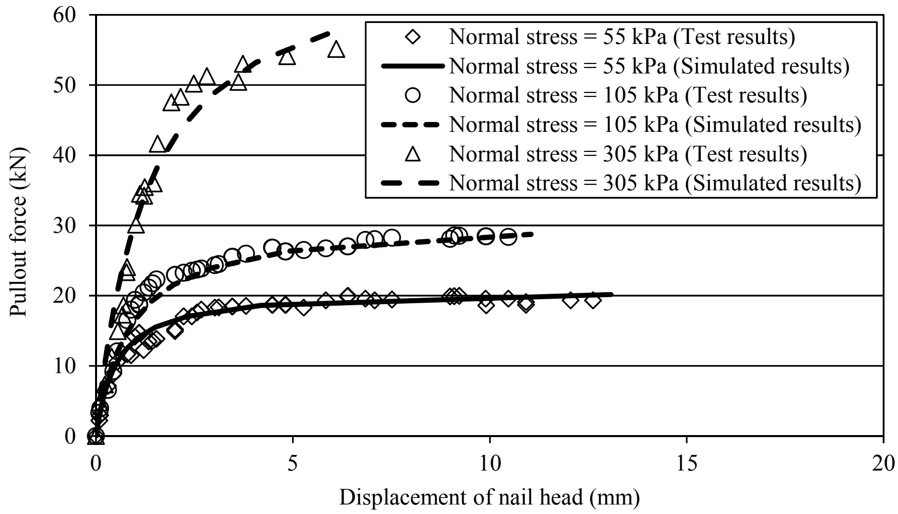
Based on the proposed hyperbolic pullout model, numerical analysis was carried out to simulate the laboratory pullout tests. The parameters used in the simulation, such as nail length L, nail diameter D, and average Young's modulus $\bar{E}$, are listed in Table 1. The other two parameters, i.e., shear resistance τ_{ult} and shear coefficient G^*_0 of the soil-grout interface, vary with normal stress, degree of saturation of the soil and surface roughness of the soil nails, which will be

Table 1 Parameters used for simulating the soil nail pullout tests (Chu and Yin 2005a, b)

Soil nail type	Length L (m)	Nail diameter D (mm)	Steel bar diameter D_s (mm)	Average Young's modulus $\overline{E}$ (GPa)
Regular surface	0.5	100	32	35.69
Irregular surface	0.7			



(a) Soil nails with regular surface roughness



(b) Soil nails with irregular surface roughness

Fig. 4 Comparison between simulated and test results with the same S_r of 70% (data from Chu and Yin 2005a, b) comprehensively analyzed in Section 4. The fitting results for the curves of pullout force versus displacement are shown in Figs. 4-6. The test results from Chu and Yin (2005a, b) show that most of the soil nails have shown significant softening behavior after the peak pullout force occurred. As this study concerns the working condition of a soil nail under pullout loads, the load-deformation behavior in the softening stage is not considered and only the pre-failure stage was analyzed using the hyperbolic pullout model.

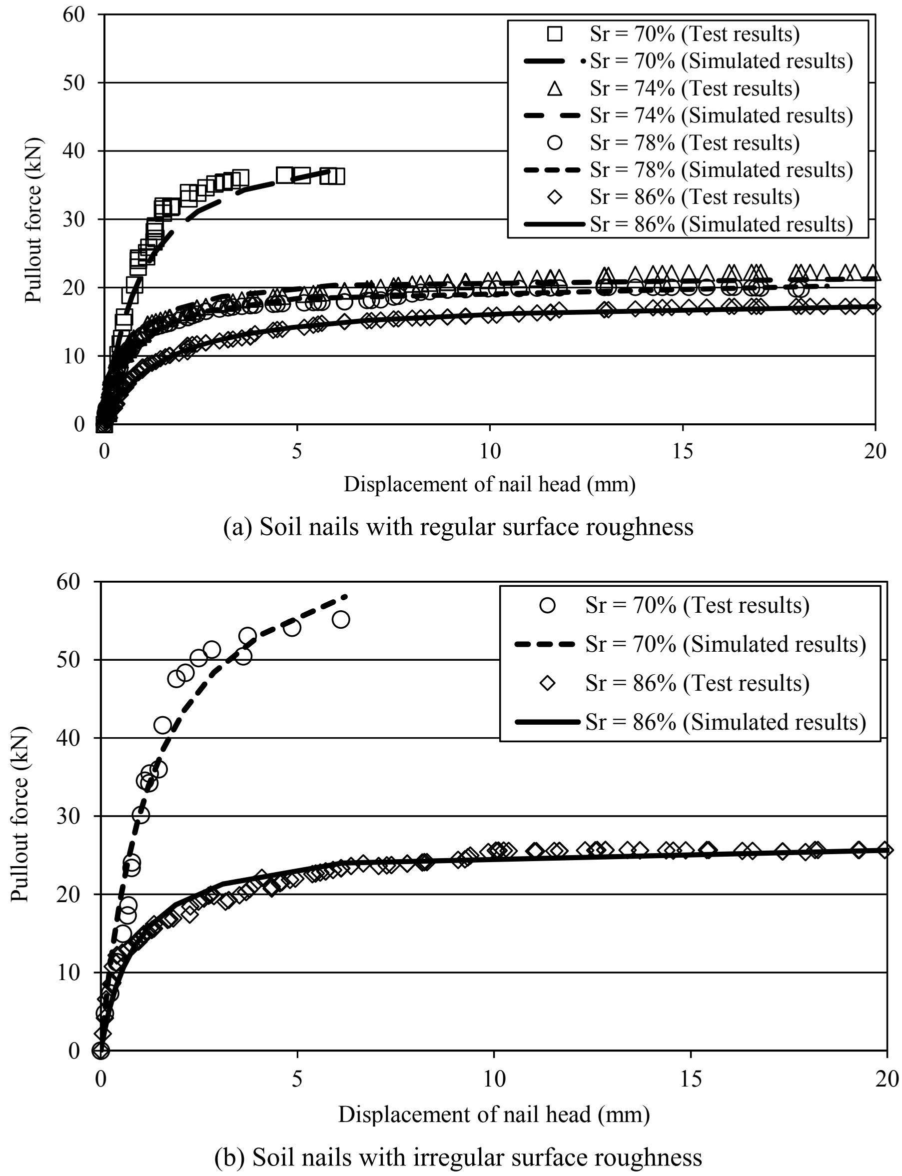


Fig. 5 Comparison between simulated and test results with the same normal stress of 300 kPa (data from Chu and Yin 2005a, b)

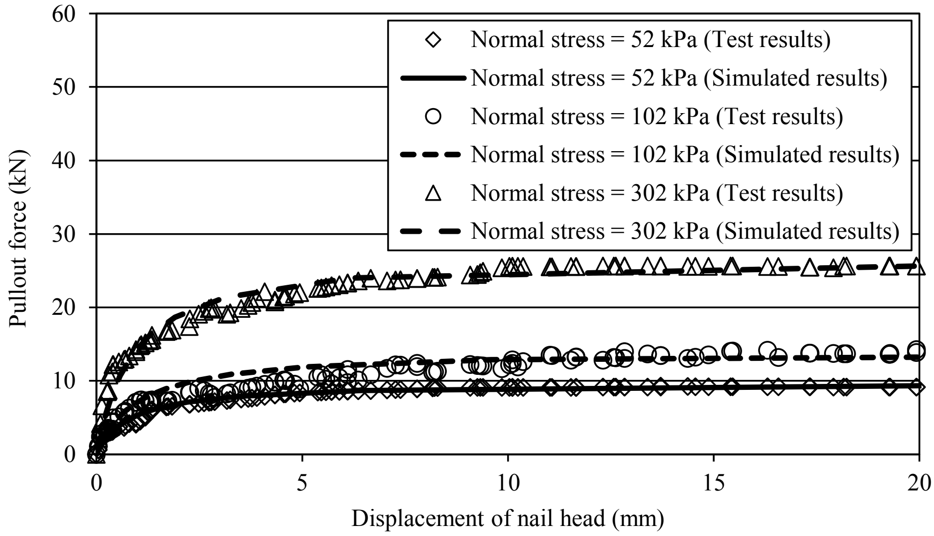


Fig. 6 Comparison between simulated and test results with the same S_r of 86% and irregular nail surface (data from Chu and Yin 2005a, b)

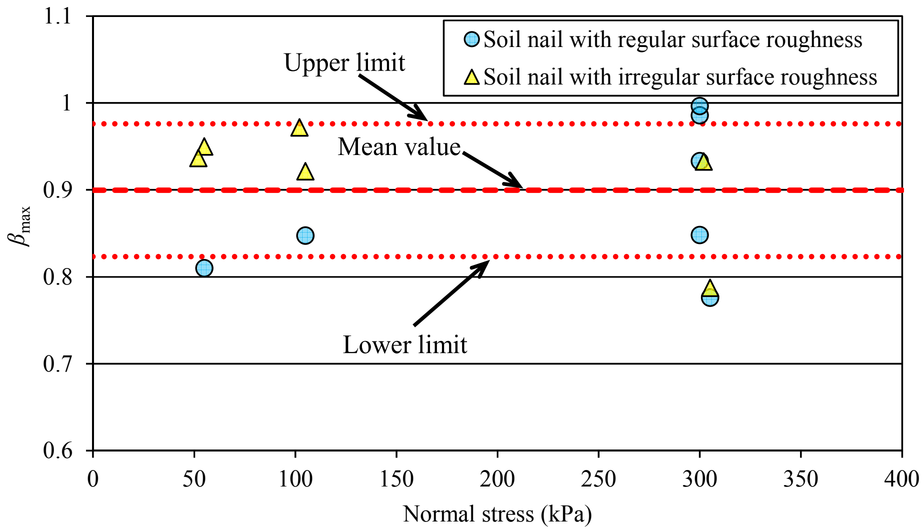
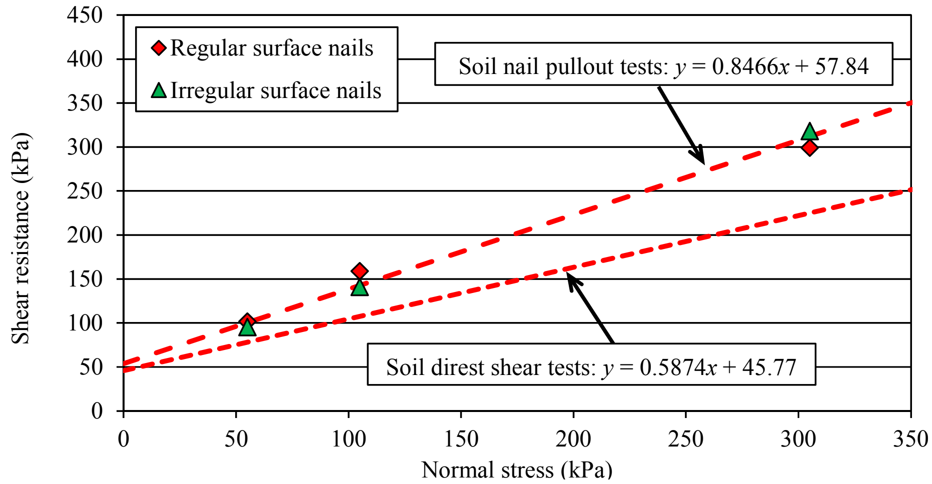


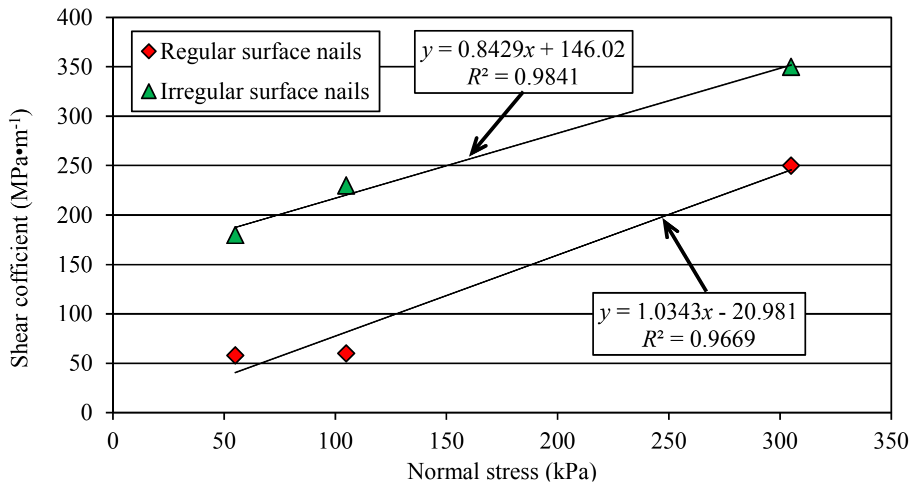
Fig. 7 Values of β_{max} obtained from the soil nail pullout test results

It is clear that the results of the proposed model are essentially consistent with those obtained from the laboratory pullout tests. It may be concluded that the previous analysis of the interaction mechanism at the soil-grout interface is rational, and the proposed pullout model can serve as an effective method to quantitatively describe the pullout performance of a soil nail.

In addition to the fitting results, some conclusions about the value of β_{max} are also drawn. As shown in Fig. 7, the values of β_{max} are found to be independent of the normal stress or the surface



(a) Shear resistance of the soil-nail interface



(b) Shear coefficient of the soil-nail interface

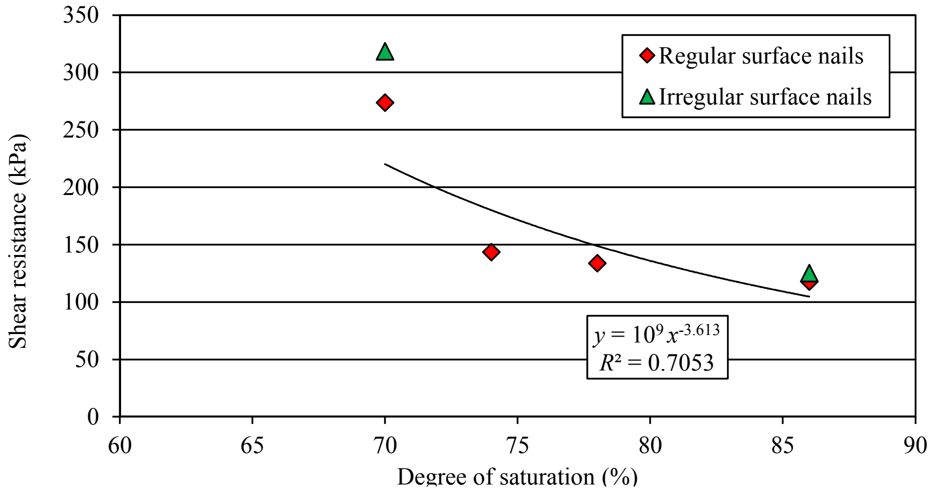
Fig. 8 Correlation between model parameters and normal stress with different surface roughness in a natural wet condition (S_r = 70%)

roughness of soil nails. The mean value and standard deviation of β_{max} are 0.90 and 0.076, respectively. Taking significance level as 5%, the p-value is calculated to be higher than 0.05, indicating that β_{max} appears to follow a normal distribution with about 68% possibility lying in the range of 0.82 and 0.98.

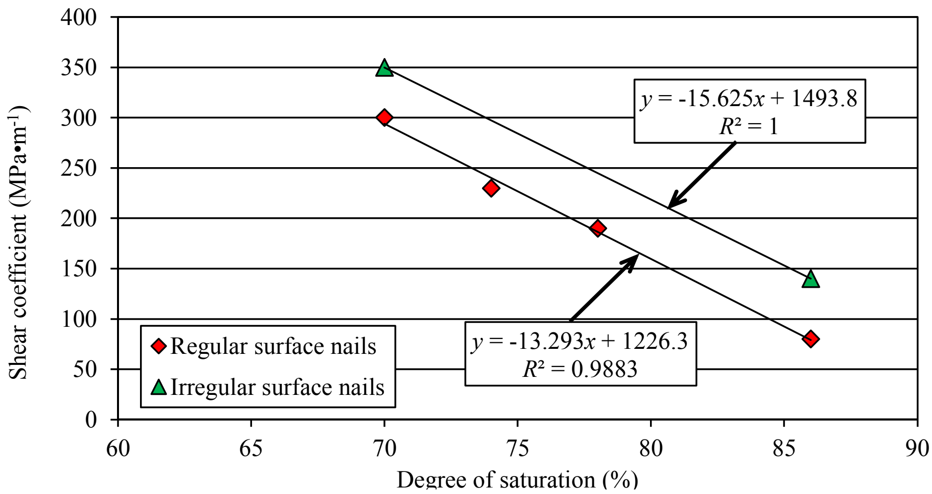
4. Influences of some key factors on model parameters

4.1 Normal stress and surface roughness of soil nail

Fig. 8 shows the variations of pullout model parameters with normal stress and surface roughness of soil nails. It is found that the shear resistance is approximately proportional to the normal stress for both regular and irregular soil nails. The surface roughness at the soil-grout interface seems not to play an important role in governing the magnitude of shear resistance, indicating the failure surface does not occur at the interface, but in the adjacent soil. The apparent friction angle (ϕ'_P = arctan (0.8466) = 40.25°) of the soil-grout interface is obviously larger than the internal friction angle ϕ_{DS}' = arctan (0.5874) = 30.43° obtained from direct shear tests on CDG soil samples.



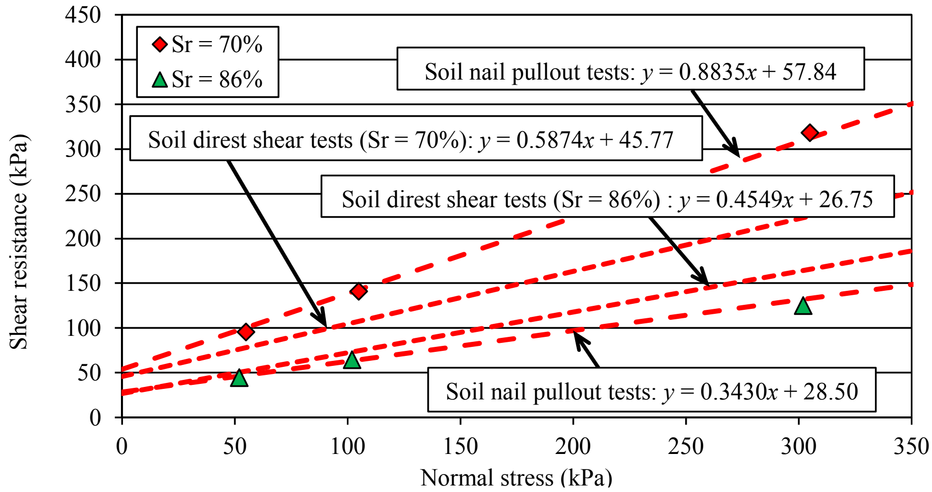
(a) Shear resistance of the soil-nail interface



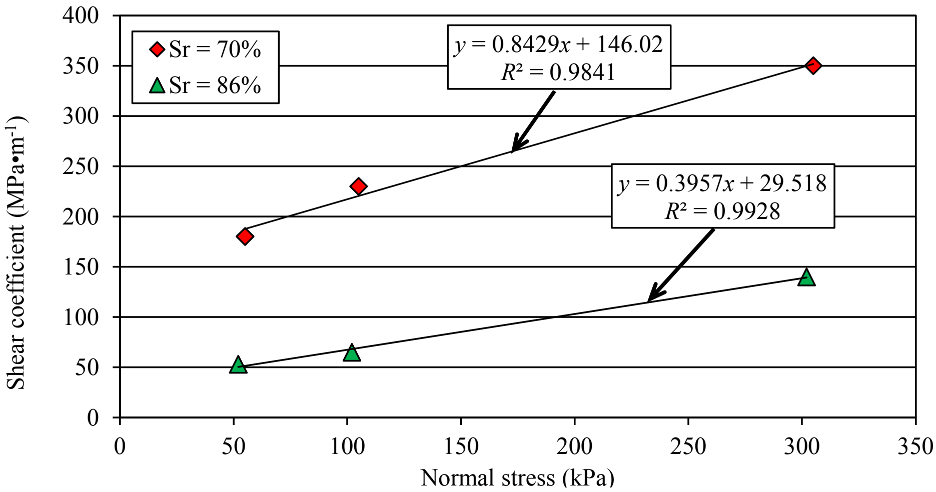
(b) Shear coefficient of the soil-nail interface

Fig. 9 Correlation between model parameters and degree of saturation with different surface roughness under the normal stress of 300 kPa

The shear coefficient of the soil-grout interface also has a close relationship with the normal stress. The shear coefficient increases with the increase in normal stress. The shear coefficient for an irregular nail is almost 3-4 times of that of a regular nail when the normal stress is low. However, when the normal stress increases to 305 kPa, the difference becomes smaller. It is indicated that the surface roughness of soil-grout interface is of great importance for preventing excessive deformation of soil nailed slopes.



(a) Shear resistance of the soil-nail interface



(b) Shear coefficient of the soil-nail interface

Fig. 10 Correlation between model parameters (irregular nails) and normal stress under the degrees of saturation of 70% and 86%

4.2 Degree of saturation of soil

Similar to the analysis of the previous section, the effect of degree of saturation of the CDG soil on the model parameters are examined. As shown in Fig. 9, there is a nonlinear relationship between shear resistance and degree of saturation of the soil. For regular soil nails, when the degree of saturation of the soil increases from 70% (natural wet condition) to 86% (submerged condition), the shear resistance is only 43.02% of that of the natural wet condition. For irregular soil nails, there will be a decrease of 60.71%. That means, if the field soil nail pullout tests are performed in dry weather condition, the design parameters based on the pullout test results will be considerably overestimated. Therefore, it is suggested that the field soil nail pullout test results should be carefully analyzed and a safety factor between the field measured pullout resistance and the design value is recommended to be introduced to account for this effect, say 2.5 or 3.0.

The shear coefficient also decreases as the degree of saturation increases. From the results of regular nails, a linear relationship can be obtained. The shear coefficients of irregular nails are slightly higher than those of regular nails given the same degree of saturation.

Fig. 10 shows the variations of model parameters of irregular soil nails with normal stress under the degrees of saturation of 70% and 86%. It is clear that the proportional relationship between shear resistance and normal stress remain applicable when the degree of saturation equals 86%. However, the apparent friction angle obtained here is ϕ'_P = arctan (0.3430) = 18.93° and is lower than the internal friction angle (ϕ_{DS}' = arctan (0.4549) = 24.46°) obtained from direct shear tests for soil samples at the same degree of saturation, in contrast to that under a natural wet condition (see Fig. 8(a)). Similarly, there is also a linear relationship between shear coefficient of soil-grout interface and normal stress when the soil is in submerged condition.

5. Conclusions

A hyperbolic pullout model was proposed to study the pullout performance of soil nails. Influences of two parameters of the derived governing equation on the distribution of normalized tensile force were analyzed. In order to verify the effectiveness of the proposed model, the calculated results were used to fit the laboratory pullout test results from Chu and Yin (2005a,b). In addition, effects of certain factors on the model parameters were investigated. The main conclusions of the present paper can be summarized as follows.

(1) Interaction mechanism at the soil-grout interface during pullout is analyzed. A soil nail pullout model is proposed on the basis of a hyperbolic relationship between interface shear stress and strain. From a parametric study, it is found that the two dimensionless parameters of the derived governing equation contribute significantly to the distribution pattern of tensile force along the nail length.

(2) The numerical results obtained by the proposed model were compared with measurements derived from laboratory soil nail pullout tests from Chu and Yin (2005a, b). It has been shown that this procedure can be successfully used for predicting the load-deformation behavior of a soil nail under pullout conditions. As the method can be easily coded or solved with the aid of a computer spreadsheet, reasonable predictions can be made without expensive and time-consuming analyses.

(3) The two model parameters, i.e. shear resistance and shear coefficient of the soil-grout interface, increase with an increase in normal stress and surface roughness of soil nail,

while they decrease with increasing degree of saturation of soil. It is indicated that increasing the surface roughness of the soil-grout interface can prevent excessive deformation of a soil nailed slope. As the pullout tests are normally performed in dry weather condition, the soil nail pullout test results should be carefully interpreted in order to perform a safe soil nail design.

It should be noted that the present model cannot accurately describe the softening pullout behavior of soil nails characterized by a decrease in the curve of pullout force versus displacement. Besides, the variations of model parameters with the normal stress, degree of saturation of soil and surface roughness of soil nails are based on the fitting results for laboratory pullout tests conducted by Chu and Yin (2005a, b). More fitting work should be done to gain a better understanding of these influences.

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