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Investigation of Effective Parameters on Pullout Capacity in Soil Nailing with Special Attention to International Design Codes

R. Ziaie Moayed, M. Mortezaee

Abstract**—**An important and influential factor in design and determining the safety factor in Soil Nailing is the ultimate pullout capacity, or, in other words, bond strength. This important parameter depends on several factors such as material and soil texture, method of implementation, excavation diameter, friction angle between the nail and the soil, grouting pressure, the nail depth (overburden pressure), the angle of drilling and the degree of saturation in soil. Federal Highway Administration (FHWA), a customary regulation in the design of nailing, is considered only the effect of the soil type (or rock) and the method of implementation in determining the bond strength, which results in non-economic design. The other regulations are each of a kind, some of the parameters affecting bond resistance are not taken into account. Therefore, in the present paper, at first the relationships and tables presented by several valid regulations are presented for estimating the ultimate pullout capacity, and then the effect of several important factors affecting on ultimate Pullout capacity are studied. Finally, it was determined, the effect of overburden pressure (in method of injection with pressure), soil dilatation and roughness of the drilling surface on pullout strength is incremental, and effect of degree of soil saturation on pullout strength to a certain degree of saturation is increasing and then decreasing. therefore it is better to get help from nail pullout-strength test results and numerical modeling to evaluate the effect of parameters such as overburden pressure, dilatation, and degree of soil saturation, and so on to reach an optimal and economical design.

Keywords**—**Soil nailing, pullout capacity, FHWA, grout.

I. INTRODUCTION

NAIL Pullout Capacity (NPC) is an important factor in the analysis and design of nailed walls, which is obtained considering the size of the nail (i.e., the diameter and the length of the nail) and the adhesive strength (bond resistance. Bond resistance can be defined as the mobilized resistance along the joint surface of the soil and injectable grout. This parameter is rarely measured in the laboratory and lacks a specific laboratory standard process. Thus, at design stage, the designer engineer (considering the field and soil conditions) usually assumes it and then the pullout of the nail is modified by testing. The only point that can be mentioned with certainty is that NPC increases with the increase in bond strength. Hence, any factor contributing to the increase in the bond strength will increase NPC as well.

R. Ziaie Moayed is the Associate Professor in Department of Civil Engineering, Imam Khomeini International University, Qazvin, Iran (phone: +982833901104; e-mail: Ziaie@eng.ikiu.ac.ir).

M. Mortezaee is Ph.D candidate in Department of Civil Engineering, Imam Khomeini International University, Qazvin, Iran (phone: +989121891247; e-mail: Mortezaee_m06@yahoo.com).

Currently, engineers and researchers have enough knowledge of the parameters affecting pullout capacity. In a holistic view, one can classify these parameters into three general categories. They are 1) soil conditions around the nail (e.g. stress relief during drilling, overburden effect, soil dilatation, the effect of arching in the nail surface due to soil and nails hardness difference and the amount of water in the soil and soil properties. Number 2 is the method of installation and implementation of the nail (installing by driving or by injection, the effect of injection pressure and the angle of the nail execution) and 3) nail profile (such as nail surface roughness). Since 1980, different equations and tables have been proposed for the analytical study of pullout resistance. In these studies, the vertical stress on the nail surface, the coefficient of friction between the nails and surrounding soil, the bond between the nails and the soil, and the soil dilatation effects have been considered. Next section presents some of these equations.

II. ANALYTICAL EQUATIONS PRESENTED TO PREDICT THE ULTIMATE PULLOUT STRENGTH

Wang and Richwein presented an analytical equation to estimate the ultimate pullout strength [1]:

$$\tau_f = \frac{f}{1-\left[2(1+\nu)/(1-2\nu)(1+2k_0)\right] f \tan\psi}\sigma_m \tag{1}$$

where f is the friction coefficient obtained from the direct shear test, υ is the Poisson ratio, σ_m is the vertical stress, and Ψ and k_0 are the dilatation angle and the lateral pressure coefficient of the soil, respectively,

Zhang et al. proposed an analytical equation for predicting the ultimate pullout strength considering soil suction and the dilatation angle [2]:

$$P_{ult} = \pi D\left[c' + (u_a - u_w)\tan\varphi^b\right] + \frac{2D\sigma_v' \tan\varphi'}{1-\dfrac{2(1+\upsilon)}{(1-2\upsilon)(1+2k_0)\tan\varphi'\tan\psi}} \tag{2}$$

where c' is the soil adhesion, u_a and u_w are the air and water cavity pressure, respectively, φ_b is the share of matric suction in shear strength, k_0, σ_v and ψ are the coefficient of lateral soil pressure, vertical stress, and soil dilatation angle respectively,

Considering the overburden effect, The Hong Kong soil-nail design system regulation (GEOGUIDE7) has presented (3) for estimating the pullout strength [3]

$$T_{ult} = \frac{\left(P_c C' + 2D\sigma'_v \mu^*\right)L}{F_{SG}} \quad (3)$$

In (3), L is the length of the nail in the resistant area (passive), μ* is the apparent friction coefficient of the soil, P_c is the area around the nail, C' is the effective adhesion of the soil, D is the outer diameter of the grout coating, σ_v is the vertical stress in the middle depth of the nail-soil from the surface of the nailed wall and F_{SG} is the pullout coefficient due to the shared collapse between the soil and grout.

The American FHWA has presented (4) to estimate the ultimate strength of the nail-soil pullout. In this equation, Q_{ult} is the ultimate pullout strength in length unit, q_u is ultimate bond strength and D_{DH} is the average drilled diameter [4].

$$Q_{ult} = \pi\, q_u\, D_{DH} \quad (4)$$

Q_u depends on factors like the method of soil-nail implementation and the type of soil. In Fig. 2, Elias and Juran present the values of q_u for different soils [5]. Fig. 1 shows the shear stresses mobilized in the joint soil and grout area and the distribution of tensile strength of the nail-soil.

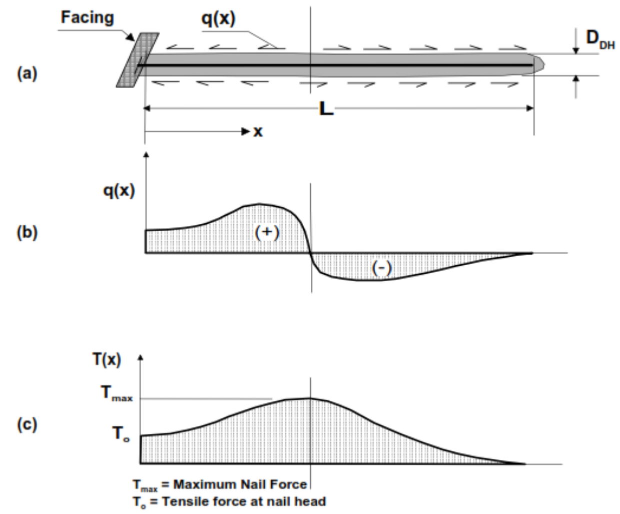

Fig. 1 Soil nail stress-transfer mechanism: a) mobilized shear stress (q) along the grout-soil interface b) diagram of mobilized shear stress c) schematic distribution of the tensile force (T) along the soil nail [4]

III. Parameters Affecting the Nail Pullout Strength

As already mentioned, many factors affect the pullout strength of the nail, each of which can affect the value of this parameter in some way. Some of the most important and influential parameters affecting bond resistance are examined from the regulations and individuals' point of view.

A. Overburden Pressure Effect

Many analytical methods connect the vertical stress of the nail surface to overburden pressure. In an effective stress system in Hong Kong, σ_n is considered equal to the equivalent Overburden at the mean depth of the nail in the resilient area, with a maximum value of 300 kPa [6]. In the UK method, the effective stress on the nail environment is determined by calculating effective Overburden using the lateral pressure coefficient of the soil. Jewell et al. suggested that the effective vertical stress on steep slopes with slightly reinforced soils could be considered between 0.7 and 1 times σ_v. [7]. However, Schlosser admitted that the actual vertical pressure largely and depends on the nail installation method. For driven nails, it is equal to the overburden pressure and for the grouted nails, this value is very small due to the release of stress during the drilling [8].

Material	Construction Method	Soil/Rock Type	Ultimate Bond Strength, q_u (kPa)
Rock	Rotary Drilled	Marl/limestone	300 - 400
		Phyllite	100 - 300
		Chalk	500 - 600
		Soft dolomite	400 - 600
		Fissured dolomite	600 - 1000
		Weathered sandstone	200 - 300
		Weathered shale	100 - 150
		Weathered schist	100 - 175
		Basalt	500 - 600
		Slate/Hard shale	300 - 400
Cohesionless Soils	Rotary Drilled	Sand/gravel	100 - 180
		Silty sand	100 - 150
		Silt	60 - 75
		Piedmont residual	40 - 120
		Fine colluvium	75 - 150
	Driven Casing	Sand/gravel	
		low overburden	190 - 240
		high overburden	280 - 430
		Dense Moraine	380 - 480
		Colluvium	100 - 180
	Augered	Silty sand fill	20 - 40
		Silty fine sand	55 - 90
		Silty clayey sand	60 - 140
	Jet Grouted	Sand	380
		Sand/gravel	700
Fine-Grained Soils	Rotary Drilled	Silty clay	35 - 50
	Driven Casing	Clayey silt	90 - 140
	Augered	Loess	25 - 75
		Soft clay	20 - 30
		Stiff clay	40 - 60
		Stiff clayey silt	40 - 100
		Calcareous sandy clay	90 - 140

Fig. 2 Estimated bond strength of soil nails in soil and rock [5]

Su and Su et al. conducted some studies on the effect of wall drilling and overburden on the strength of nail pullout in loose granite soils [9], [10]. These studies have shown that the drilling of the walls will have a significant reduction in tension and, if using non-pressure grout, the pullout strength will not be related to overburden pressure. Fig. 3 clearly shows this lack of dependence.

B. Effect of Soil Dilatation

Many studies have been conducted on the effect of soil dilatation on pullout strength. The results show a significant effect of pullout strength [8], [11].

Schlosser found that pullout strength in sandy soils was significantly dependent on the soil's dilatation behavior. Sandy soils with high density tend to be dilated until they were cut off. On the other hand, the existence of the surrounding soils plays an important role and prevents the volume of the soil from being subjected to shear, so the vertical pressure on the nails will increase due to the surrounding soil reaction [8]. This increase in stress in some cases is four times the initial stress, which is shown in Fig. 4.

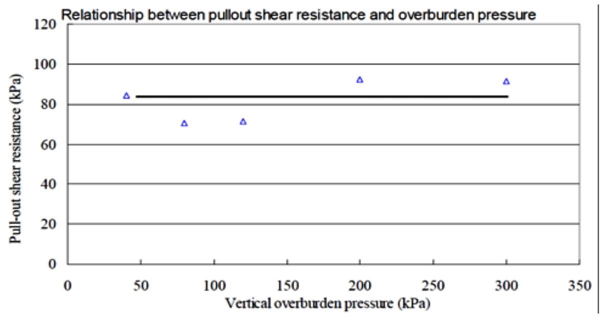

Fig. 3 Effect of overburden pressure and wall drilling on pullout strength [10]

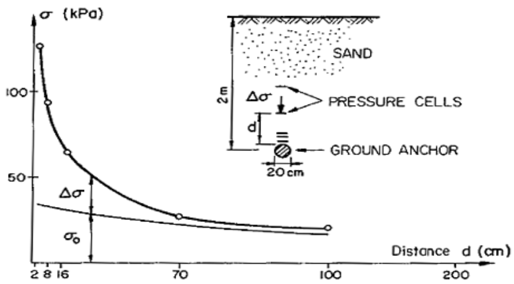

Fig. 4 Effect of increasing vertical stress due to the limitation of swelling by the soils surrounding the nails [11]

The value of this stress increase depends on the parameters such as enclosing pressure, relative density of soil, grain size and shape, and its saturation conditions. Increase in the overburden pressure causes increases enclosure pressure and reduces the tendency of the soil to swell. Laboratory and large-scale experiments indicated that the wall friction does not depend on depth, and the effect of swelling limiting soils is compensated by increasing overburden pressure [11]. Normally, the dilatation phenomenon is considered in high-density sandy soils is considered and is not found in loose soils. In the pullout test on dense sandy soil, the vertical pressure around the soil and the nail significantly increases during pullout, but in case of saturation, this will not happen much.

C. Effect of Degree of Soil Saturation

Soil saturation is another factor affecting pullout strength. The existence of water in the joint soil-nail area, especially the plastic soils, creates lubricating effect and reduces pullout strength largely. Various studies have been conducted on the effect of the degree of saturation on the pullout strength of the nails [12], [13]. Very little strength has been reported for fully saturated soils. Su et al. performed pullout experiments on sedimentary granitic soils with different degrees of saturation and overburden [14]. They saw that in different states of the degree of saturation and Overburden Pressure, position of the rupture changed (Fig. 5). As is seen, the ultimate pullout strength increases to a certain extent with increase in saturation and then decreases.

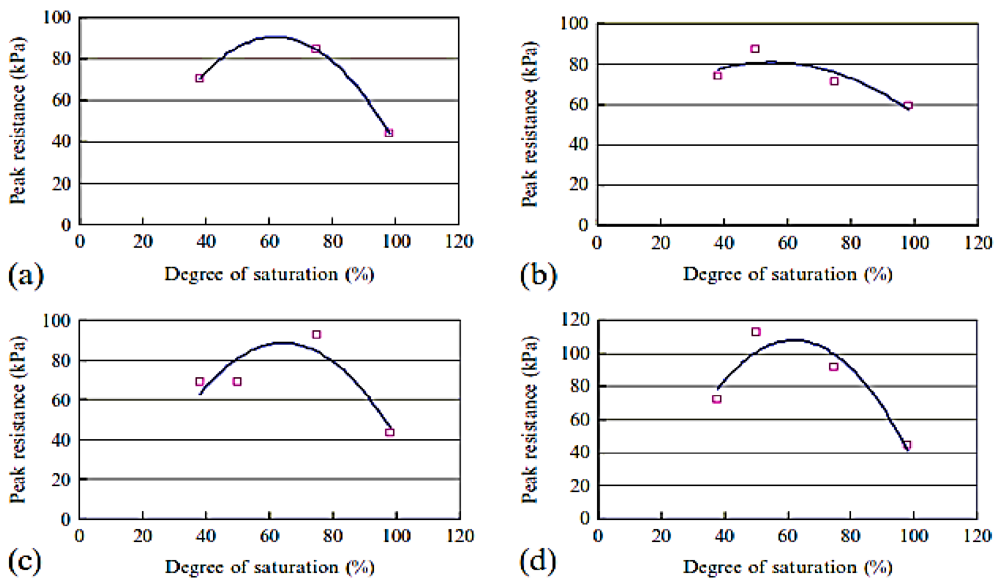

Fig. 5 The relationship between ultimate pullout strength and degree of saturation with Overburden pressures of (a) 40 kPa (b) 120 kPa (c) 200 kPa and (d) 300 kPa [14]

D. Effect Installation and Implementation Method

The method of installing soil nailing is carried out in two ways: driving and drilling. In drilling method, two injection methods are usable. The first method is done using a tremie tube and without pressure tube and the second is injection with pressure, both of which have a significant effect on vertical stress and ultimate pullout resistance [15].

1) Effect of Installation with Driving Method

Studies have shown that in the driving method the pullout strength increases with increase in the volume of the element inserted into the soil. The reason for this increase is increase in the density during punching and increase the stress on the soil-nail surrounding. A similar behavior has been reported in driving piles [16].

2) Effect of the Installation with the Insertion of Rebar

The dimensions of the drilling performed for soil-nail placement, the characteristics of the injectable grout, and the type of injection have a significant effect on the pullout strength of the soil-nails. In this method, the properties of the soil-nail around as well as the vertical tension in the contact area and the soil and roughness between the surfaces are directly affected by the installation and implementation of the nail [16].

3) Effect of Injection without Pressure with Tremie Tube

The injection of concrete using a tremie tube typically has a very small effect on the tensile strength of the contact surface and the tensile strength of the tensile member. If the grout is used, the drilling of the walls will have the effect of not loading of the soil around the nail and will significantly affect its mechanical properties. The interaction between the soil and the nail can greatly depend on re-density of soil due to the grout. According to the studies conducted, the difference in pullout strength in the injection with tremie tube and the injection under pressure is very significant and in the injection with pressure, strength increases substantially [17].

4) Effect of Injection with Pressure

The pressure from the grout can cause soil re-accumulation and penetrate sandy soils. Thus, it increases pullout strength considerably. The mechanical locking between the cement grout and the soil will greatly increase the bond strength, which will play a significant role in increasing the pullout strength. The bond strength between the nail and the surrounding soil depends on factors such as soil properties, roughness of the drilled surfaces and applied grout pressure. The researchers showed that in adhesive soils, low small-grain grout pressures could lead to relatively uniformity of soil-nail joint. In non-adhesive soils, the grout pressure is usually between 350 and 700 KPa, so that it does not collapse when draining the pipe of soil placement around the nail [5]. Some researchers claim that using grout pressure is an effective way to increase pullout strength [18], [19].

5) Effect of Drilled Surface

The roughness of the drilled surface affects the bond strength of the grout and soil, which will increase the pullout strength. The results show that as the wall of the hole is smoother, the pullout strength will reduce [11] and the irregularity in the formation of the hole has a positive effect on the pullout strength. This effect increases the limiting pressure of the soil around the nail and increases the vertical stresses on the nails. Pullout experiments were conducted in 1998 on the Leighton Buzzard sand with rough and smooth walls [20]. The results of these experiments showed that for holes with a smooth wall, the angle of friction relative to the roughness of the surface of the nail is much smaller and the increase in vertical tension due to the dilatation of the soil can be ignored.

IV. Conclusion

In the present paper, while describing the factors affecting the strength of the nail pullout strength, several important factors affecting this parameter are examined from the regulations and various researchers point of view.

- The effect of overburden pressure has not been seen in the FHWA Procedure, but in some codes, such as the Hong Kong procedure or the UK method, the effect of this parameter is considered. However, the results show that the effect of overburden pressure is significant (it increases the pullout strength) that the injection procedure is under pressure.
- The effect of soil dilatation on pullout strength, especially in granular soils, is significant and can increase the tension by 4 times around the nail.
- The effect of the degree of soil saturation on the pullout strength of the nail is increasing up to a degree and then decreasing. In the other words, in saturation we face the least pullout strength.
- Installing and implementation will also have a significant effect on the pullout strength of the nail. From among the different methods of nailing in the soil, the pressure injection method gives the highest pullout strength. In addition, surface roughness of the injection cavity can greatly increase pullout strength.

Considering the above and that none of the commonly used equations for pullout strength consider all the effective factors, it is better to get help from nail pullout-strength test results and numerical modeling to evaluate the effect of parameters such as overburden pressure, dilatation, and so on to reach an optimal and economical design.

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