Effect of soil type on nail pull-out resistance

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Nowadays, soil nailing is widely used to stabilize slopes and excavations. The bond strength is integrated shear strength along the interface area between grout and soil. Choosing a value for bond resistance is one of the effective parameters in nailed wall design, which is generally determined by the values proposed by FHWA guidelines. A designer uses a high safety factor that makes the design safe but sometimes it is not economical. Therefore, in this study, an attempt is made to investigate the effects of overburden, injection pressure and soil strength parameters on the bond strength of nails in field. For this research, five different sites in Tehran were considered with a total number of 20 soil–nail pull-out test. Values such as cohesion, friction angle, modulus of elasticity, moisture content, percentage of coarse- and fine-grained soil were determined in the laboratory, and the effect of these parameters on the bond strength was examined. The results of the tests showed that by increasing injection pressure and overburden height, bond strength increases, and that the effect of injection pressure is much more than that of overburden height. Finally, a relationship was suggested to estimate the bond strength in terms of soil specifications and overburden height.

1. Introduction

Nailing is a stabilisation system in excavations and slope surfaces. The main reasons for using this system are: (a) short constructing period, (b) it does not require a lot of equipment and (c) cost-effective implementation (Chu and Yin, 2005; Schlosser, 1982). Nailing was used for the first time in 1980 in Hong Kong to stabilise trenches and slope surfaces. Using this method increases the general shear strength of soil, which leads to limited displacements in the excavation walls and slopes. A soil-nailed wall consists of a number of steel bars (with typical diameter of 25–40 mm) within a drilled borehole (generally with a diameter of 100 mm and length of 4–20 m) with cement grout (usually water–cement ratio 0.42) (Chu and Yin, 2005; Junaideen *et al.*, 2004). Bond strength is integrated shear strength along the interface area between grout and soil. Bond strength is rarely measured in the laboratory and no standard for laboratory tests can be used to evaluate the bond strength (Su, 2006; Yin and Su, 2006), so only a pull-out test in the field can provide a credible estimation of bond strength. Bond strength depends on a variety of factors such as environmental conditions, the nature of grout, injection type, overburden pressure and so on.

Su *et al.* (2008) performed a series of laboratory pull-out tests on samples of completely decomposed granite (CDG) in order to evaluate the effect of overburden. These researchers found that increasing the stresses caused by overburden did not affect the pull-out resistance of gravity-injected soil–nail. This is due to the release of stress during the drilling process (Su *et al.*, 2008). Su *et al.* (2008) carried out a series of pull-out tests on a sample of CDG soil and concluded that increasing the injection pressure leads to an increase in pull-out resistance. Zhou *et al.* (2008) found that the effect of injection

pressure in samples injected under 200 kPa pressure is much more than the effect of injection pressure in samples injected under 80 kPa pressure. Also Su *et al.* (2007) carried out a series of laboratory tests on soils with saturation degrees of 38, 50, 75 and 90% to evaluate the effect of saturation. These researchers found that by increasing the saturation of soil, shear surfaces locate some distance from the nail–soil surface during pull-out tests. Therefore, in dry soil, the shear resistance of the soil–nail interface and surrounding soil is less than the shear strength of the soil. These researchers also, by experimental investigation of pull-out testing in CDG soil, found that dense samples are fractured under the influence of shearing.

In this study, the bond strength of soil is evaluated in the form of a field study. Five test sites in Tehran were considered, which included 20 samples of soil–nails. Values such as cohesion, friction angle, modulus of elasticity, moisture content and percentage of coarse- and fine-grained soils were determined in the laboratory, and the effect of these parameters on the bond strength is examined.

2. An introduction to the study area

North and north-west of Tehran are the regions in which several deep excavations occur to a depth of over 30 m every year. Therefore, in this study, pull-out tests of soil–nails in five different areas of Tehran have been carried out. Five excavation projects were examined, starting from the beginning of excavation to the end of the project. Tehran's alluvial deposits can be divided into four formation parts named A, B, C and D. Part A is the oldest formation and part D is the newest formation. In order to evaluate the bond strength between soil and grout, five sites located in Kashani street, Saadat Abad,

Figure 1. Position of test sites in this research

Table 1. Number of tests performed

Site name	Field test			Laboratory test		
	In-situ direct shear test	Pull-out test	Plate load test	Atterberg limits	Moisture content	Soil gradation
Darband	6	4	2	3	3	1
Sohanak	12	4	4	3	3	1
Pasdaran	9	4	3	3	3	1
Kashani	12	4	4	3	3	1
Saadat Abad	6	4	2	3	3	1

Darband, Sohanak and Pasdaran, which are indicated on the map provided in Figure 1 were studied. By examining the site locations, it is determined that Kashani site is located at C formation, Saadat Abad site is at B formation and three Pasdaran, Darband and Sohanak sites are at A formation.

3. Experiments conducted

To determine the parameters needed in this research, field and laboratory tests have been done on soil and soil nails. In Table 1, the number of field and laboratory experiments conducted in this study are shown.

3.1 Laboratory tests

To identify and acquire the technical and mechanical properties of subsurface materials, physical and mechanical tests were conducted in the laboratory on samples taken from the galleries in all test sites. Also disturbed samples were used to determine soil physical properties such as particle size distribution. Laboratory tests were carried out according to ASTM D 422-63 (1990). Physical properties in this study were determined using laboratory tests to establish the basic characteristics of the soil; these were conducted at the Geotechnical Laboratory in Kharazmi University of Tehran.

Table 2. The physical properties of studied soils

	Moisture content	Atterberg limits			Soil gradation		
		PI	PL	LL	Gravel content	Sand content	Fine content
Saadat Abad	9.24	14.9	19.8	34.7	44.42	49.3	6.27
Kashani	7.6	4	19.8	23.8	38.3	57.16	4.53
Sohanak	7.4	14.43	25.75	40	38.02	54.51	7.46
Pasdaran	10.54	6.6	17.2	23.8	42.79	49.68	7.52
Darband	9.52	7.5	18	25.5	37.86	56.94	5.19

PI, plasticity index; PL, plastic limit; LL, liquid limit

Table 3. Soil strength properties of various sites

	Soil parameters		Parameters of shear strength of soil	
	E : kN/m ²	γ : kN/m ³	Φ : deg	C : kN/m ²
Saadat Abad	65 000	20.2	33	7
Kashani	80 000	21	38	12
Sohanak	35 000	20	33	49
Pasdaran ($H = 5$)	35 000	20	45	2
Pasdaran ($H = 20$)	48 000	20	45	1
Darband	60 000	20.6	35	9

3.2 Field tests

The strength properties examined in this study include the parameters of shear strength, modulus of elasticity and soil density, which were estimated by plate load test, pull-out test and in situ direct shear tests. Physical properties and resistance information of the studied soil are shown in Tables 2 and 3, respectively. It should be noted that the high value of soil cohesion in the Sohanak site is due to a high degree of soil cementation.

4. Pull-out test

According to a Federal Highway Administration (FHWA) report, at least two destructive tests must be done in each layer of soil (Lazarte *et al.*, 2003). This test was performed on non-structural soil–nails (sacrifice) before installing structural soil–nails in order to assess the drilling method and review the resistance required for soil–nails. In this experiment, a part of the nail bar is not injected, of at least 1 m length. The bonded soil nail length during verification tests is at least 3 m, but it should not exceed the maximum length. In fact, the maximum effective length is achieved when the release strength of a soil–nail equals 90% of the allowable tensile strength of the nail bar Lazarte *et al.* (2003).

4.1 Sample preparation

Drilling operations are done in two levels of +4 and +8 m. The diameter of the bar used in this test is 40 mm and its properties are shown in Table 4. According to a FHWA report, the maximum tolerable force in the tensile test is $0.9f_y \times A$ (Lazarte *et al.* (2003)) where f_y is yield stress and A is the cross-sectional area of the bar. Also covered length and free

Table 4. Bar specifications

Bar specifications tested	
f_y (yield stress)	4000 kg/cm ²
A_y (cross-section area)	12.60 cm ²
E (modulus of elasticity)	12 GPa
$0.9f_y \times A$ (maximum tolerable tensile force)	55 000 kg

length are considered to be 3 and 1 m, respectively. The rotary drilling method was utilised and, in each level, two bars were embedded. One of them was injected according to the gravity-injected mode and another was injected at 200 kPa pressure.

4.2 Test procedure

According to a FHWA report, a period of 7 d is needed to reach the desired strength after drilling and grout injection, and then the sample is prepared for testing. In order to perform the test, an Enerpac 600 kN cylindrical hydraulic jack was used. The pressure gauge is calibrated according to ISO 143904-Ukas (England) (Ukas, 2006). As shown in Figure 2, the components of the jack are

- displacement gauge
- pressure gauge
- hydraulic lever pump
- cylindrical jack
- hydraulic hoses

To perform tests according to Ukas (2006), the test was carried out with constant force with 10 min rest time. At each stage of the experiment, the value of force increment was 50 kN. In Table 5, a sample of collected information is given for each experiment where q_u is the bond strength of the soil.

5. Pull-out test results

In this section, investigation and interpretation of pull-out tests results were carried out. As shown in Table 2, soils in all sites have a fine-grained percentage of <10, therefore the properties of soil plasticity are not considered. Also, considering the low groundwater levels at all sites, soil moisture changes do not affect the results. Therefore, in all soils the moisture content is assumed to be the same and an attempt is made to investigate the effect of other parameters on the bond strength.

Figure 2. Components of Enerpac jack used in the experiments of this study

5.1 Determination of bond strength

In Figure 3, the load–time curve is plotted for a nail; it can be seen that, by increasing the time, the value of force increases and, after reaching a maximum value, it is reduced. By using a load–time graph, the bond strength of grout for gravity-injected and soil nails injected under pressure can be examined. Finally, the cohesion strength of grout and soil is determined.

5.2 Examining pull-out resistance against displacement

As shown in Figures 4–8, generally the maximum pull-out resistance is related to soil–nails injected under 200 kPa pressure, which are installed at a level of 8 m. The minimum

pull-out resistance is related to gravity-injected soil–nails that are installed at a level of 4 m. It is also found that the pull-out resistance increased with increasing injection pressure and height of soil overburden. The nature of the increment suggests that the influence of injection pressure is much greater than the influence of height pressure due to overburden soil.

From the review of the Sohanak site (Figure 7) the authors found that the process of displacement changes among four soil–nails were very closely aligned. The reason for this phenomenon can be explained according to the cementation and reduction in the spaces between soil grains. Also by examining Figures 4–8, it is found that the maximum displacement is related to gravity-injected soil–nails for 250 kPa force, and the maximum displacement is related to the soil–nails injected under a pressure of 200 kPa. In Table 6, the bond strength values obtained from tensile tests are presented. The increase in bond strength under the influence of injection pressure is shown in Table 7. By examining Tables 6 and 7 it is deduced that if injection pressure is increased from zero up to 200 kPa, average bond strength increases almost 20%. The increase of the bond strength under the influence of the height pressure of overburden soil is shown in Table 8. By examining Tables 6 and 8, it is deduced that by increasing the overburden soil height from 4 to 8 m, average bond strength increased almost 7%.

5.3 Effects of various parameters on bond strength

To evaluate the effect of shear strength parameters of soil on bond strength, a cohesion diagram $q_u - (c + \gamma h \tan \phi)$ was drawn. The phrase $c + \gamma h \tan \phi$ is termed the apparent shear resistance, in which γ is soil density (kN/m^3), h is overburden height (m), c is soil cohesion (kN/m^2), ϕ is internal friction angle (degrees) and q_u is bond resistance of soil (kN/m^2). In Tables 9 and 10, the apparent shear stress and bond strength values for all samples are presented.

In Figures 9–12, diagrams of shear bond strength against apparent shear stress for gravity-injected soil–nails and

Table 5. Specification of pull-out test for a sample nail (Pasdaran site)

Nail feature		Specifications of pull-out test			
Borehole length	4 m	Load: kN	Hold: min	Gauge	Movement: mm
Drilling rod diameter	95 mm	0	10	11.38	0
Borehole diameter	110	50	10	16.41	0.28
Non-bond length	100 cm	100	10	20.69	0.38
		150	10	22.17	0.4
Unbond length	4 m	200	10	24.42	0.43
Injection pressure	Gravity	250	10	25.02	0.42
Bar number	Φ40	300	10	26.74	0.44
Water/cement ratio	0.4	350	10	28.32	1.1
Elevation from edge of wall	8	400	10	30.56	0.93
Fail load: kN				450	
Bond strength: kPa				477.7

Figure 3. Load-time sample curve in tests of this research

Figure 6. Diagram of shear stress against displacement (Darband site)

Figure 4. Diagram of shear stress plotted against displacement (Kashani site)

Figure 7. Diagram of shear stress against displacement (Sohanak site)

Figure 5. Diagram of shear stress against displacement (Saadat Abad site)

Figure 8. Diagram of shear stress against displacement (Pasdaran site)

200 kPa injection pressure soil-nails at two different depths are drawn. As can be seen, in the gravity and under-pressure states, bond strength has a linear relationship with apparent stress. In Table 11, the equation and standard deviation are shown where X is the apparent shear stress. By examining the values of standard deviation, the authors found that the standard deviation of the current equation for gravity-injected soil-nails has good agreement with values obtained from field

experiments. In general, for similar soil samples having an apparent shear stress, bond strength can be determined using these equations for heights of 4 and 8 m. By increasing injection pressure from 0 to 200 kPa, slope and Y intercept values for each of the equations increased, which could be due to the influence of injection pressure on bond strength.

Table 6. Bond strength values obtained from tensile test

Site name	Soil–nail specifications and injection conditions			
	$H = 4$ m		$H = 8$ m	
	$P = 200$ kPa: kPa	Gravity: kPa	$P = 200$ kPa: kPa	Gravity: kPa
Saadat Abad	424	357	467	382
Kashani	452	396	474	402
Sohanak	515	443	583	463
Pasdaran	525	436	614	434
Darband	414	366	472	386

Table 7. Increase of bond strength under the influence of injection pressure

Site name	Increase of bond strength: %	
	$H = 4$ m	$H = 8$ m
Saadat Abad	18	27
Kashani	14	19
Sohanak	16	25
Pasdaran	20	28
Darband	13	15

Table 8. Increase of bond strength under the influence of overburden soil height

Site name	Increase of bond strength: %	
	(GP = 0 kPa)	(GP = 200 kPa)
Saadat Abad	2.5	10
Kashani	1.5	5
Sohanak	4.5	12
Pasdaran	8.6	14
Darband	5.3	8

6. Comparison of the results of this study with the results of other researchers

In this section, the results of this study are compared with the results of other researchers and valid reports such as the Elias and Juran (1991) and Lazarte *et al.* (2003).

- The results of this study show that, by increasing the time at each stage, the value of force increases, and after achieving a maximum the value of force decreases. This peak point is defined as the bond strength. This issue was experimentally examined by researchers such as Su *et al.* (2008), Yin and Zhou (2009) and Zhou *et al.* (2007), and they obtained similar results.
- The results of this research show that, by increasing the pressure up to 200 kPa, bond strength is increased about 20%. This issue was studied by researchers such as Elias and Juran (1991). These researchers found that, by increasing the injection pressure up to 350 kPa, bond strength increased up to double. Other researchers such as Yin *et al.* (2012), Zhou *et al.* (2007) and Zhou *et al.* (2010)

Table 9. Numerical values of pull-out resistance at five different sites for depth of 8 m

Site name	Bond strength (under pressure 200 kPa)	Cohesion strength (gravity state)	$C + \gamma h$ (tan Φ)
Saadat Abad	467	366	111.94
Niavarani	472	386	124.39
Kashani	478	401	143.26
Pasdaran	614	500	170.00
Sohanak	583	463	153.00

Table 10. Numerical values of pull-out resistance at five different sites for depth of 4 m

Site name	Bond strength (under pressure 200 kPa)	Cohesion strength (gravity state)	Apparent shear stress $C + \gamma h$ (tan Φ)
Saadat Abad	424	357	59.47
Niavarani	414	366	66.70
Kashani	452	396	77.63
Pasdaran	525	436	82.00
Sohanak	515	443	100.95

studied the effect of the injection pressure and all of them concluded that the bond strength increases by increasing injection pressure.

Zhou *et al.* (2010) found that, by increasing the injection pressure from 250 to 350 kPa, the bond strength would increase about 80%. Yin and Zhou (2009) concluded that the effect of injection pressure on the shear strength in pressures <130 kPa is almost negligible, but by increasing injection pressure up to 250 kPa the cohesion strength increases almost 25%.

- The results of this study show that, according to the field tests, by changing overburden height up to 4 m, the bond strength is not much changed; however, researchers such as Su *et al.* (2007) investigated the simultaneous effects of the injection pressure and overburden. The results of these researchers showed that by increasing overburden pressure the bond strength of soil–nails increases, but in the gravity-injected soil–nails the bond strength does not increase owing to a release of stress while drilling.

Figure 9. The relationship between shear strength parameters and bond strength ($h = 4$ m, gravity)

Figure 11. The relationship between shear strength parameters and bond strength ($h = 4$ m, $p = 200$ kPa)

Figure 10. The relationship between shear strength parameters and bond strength ($h = 8$ m, gravity)

Figure 12. The relationship between shear strength parameters and bond strength ($h = 8$ m, $p = 200$ kPa)

7. Conclusions

In this study, a series of field tests on five soil samples was carried out to determine the effects of overburden pressure, injection pressure and basic characteristics of the soil on nail pull-out strength. The results obtained can be summarised as follows.

- By increasing the steps at each stage the value of the force increases and, after achieving the maximum force, the value of the force decreases.
- By increasing the injection pressure up to 200 kPa, the average bond strength increases about 20%. However, when increasing the depth (overburden) from 4 to 8 m the bond strength increment is almost negligible (about 7%).

Table 11. Equation and standard deviation of relationships between bond strength and apparent shear stress

Site name	Bond strength (under pressure 200 kPa)	Cohesion strength (gravity state)	Apparent shear stress $C + \gamma h (\tan \Phi)$
Saadat Abad	424	357	59.47
Niavarani	414	366	66.70
Kashani	452	396	77.63
Pasdarani	525	436	82.00
Sohanak	515	443	100.95

- Maximum displacement occurs for a force of 250 kPa related to the gravity-injected soil–nails, and maximum displacement occurs related to soil–nails under a pressure of 200 kPa.

- For all soil–nails the apparent shear stress has a linear relationship with bond strength, so for similar soil samples undergoing apparent shear stress, bond strength can be determined.
- In cemented soils, displacement of soil–nails under pull-out testing is the same for both gravity and pressure injection modes.

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