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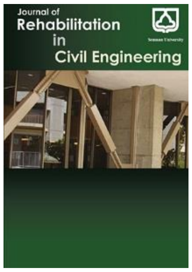

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Study of Nail Group Efficiency on Sandy Soil Using Large Scale Pull-Out Box

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ABSTRACT

The present study aims at investigating the pull-out resistance efficiency of single and double nails. In sandy soils, where the distance between nails is less than the minimum required distance, the pull-out resistance is reduced. Besides, when the minimum required distance is met, the nail pull-out capacity is not under the effect of the neighboring nail. The parameters affecting the efficiency of the nail group are investigated in this study; including, a type of nail, nail intervals and overburden type of pressure. One of the most important parameters – in order to determine the efficiency of the group – is the nail surface roughness coefficient, which is dependent on factors such as the number of the ribs in each unit length of nail and, also, the depth of the ribs to the size of soil particle. The nail surface roughness coefficient is used to determine the apparent friction coefficient on the nail surface. In all tests, the pull-out force-displacement curve had distinct peak values, accompanied by a reduction in the pull-out force value. The results indicated that the minimum distance required for the full involvement of the pull-out resistance of the nails was strongly subservient to the roughness coefficient of the nail surface.

1. Introduction

Soil nailing walls are considered to be alternatives for maintenance systems such as tieback soldier piles and ordinary retaining walls. They are widely used in stabilizing and sloping roads and highways, reinforcing bridges, stabilizing tunnels, and repairing the existing structures [5]. In this method, the nails are placed close together in the soil whereby they form a reinforced soil structure. These nails can be described as tension and slender members made of metal

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or polymer materials. One of the advantages of this method is the flexibility of the soil nailing structure, as well as reducing the cost and time of project implementation. The laboratory tests and numerical analyses in this field suggest that nail analysis is primarily based on axial force control [15, 16, 20, and 23].

The main concern regarding the design of soil nailing is the pull-out resistance or the bond strength between the soil and the nail. This parameter estimation in the designs is influenced by the distance between the nails, the nail diameter and length, and the final bond strength between soil and nail. In this sense, understanding how resistance develops at the interface between soil and nail interface is one of the most important problems on which various researchers have worked on [4, 9, 10, 17, 19, 22, 29, 30, 32, 33, and 34]. There is no comprehensive method estimating the final strength of the bond between soil and nail. In this regard, it is worth mentioning that designs are relied on the estimated values of experimental studies by in situ tests and experiences. Meanwhile, the pull-out capacity of soil nails can be under the influence of the interactions of the neighboring nail. The nail pull-out resistance in sandy soil may be less than the capacity actually determined. In order to overcome this problem, the nail pull-out capacity should be modified.

Many designers tend to use a database compiled from the results of other researchers' pull-out tests to measure pull-out resistance. Elias and Juran considered the final pull-out stresses as the soil type and installation method function and, then, attempted to relate pull-out resistance to soil properties using routine in-situ tests [3].

Schlosser stated, in the French National Project (Clouterre), that pull-out resistance is correlated with the confined pressure measured by the installation of a stress gage. The pull-out resistance measured, in situ for reasons such as the ground conditions and effective nail size, changes in the ground stress during installation of nail, while changes in the around stress around the nails during the pull-out test often overestimate the values [25, 26].

Chu and Yin (2005) performed laboratory tests on the pull-out with the grouted soil nail in Completely Decomposed Granite (CDG) soil in a box measuring 70 * 56 * 60.5 cm (length * width * height). The researchers investigated the soil saturation effect (degree of saturation) and overburden pressure on the pull-out resistance. The results indicated that the force-displacement curves show a significant peak at the shear strength behavior and beyond for the pull-out tests of the shear strength behavior [2].

Junaideen et al. claimed that there is no procedural unity in the estimation of pull-out resistance and came to this conclusion that the pull-out tests, implemented by designers and researchers, are the simplest and the best ones in hand. The researchers used a pull-out box measuring 200 * 160 * 140 cm (length * width * height) in their studies. They performed tests on different types of bars with different surcharges and showed that the pull-out resistance is affected by rib of the bars. In addition, there is mobilization of the pull-out forces within the first few millimeters of the nail displacement. Besides, the load-displacement curves have distinct peak values, after which it diminishes dramatically [17].

Hong et al. implemented tests in field and laboratory to examine the effects of grouting and overburden pressure on regular grouting nails. They discovered that the pull-out resistance showed an increasing linear relationship with grouting pressure, but the overburden pressure did not affect the pull-out capacity [12]. On the other hand, Yin and Zhou performed specific laboratory studies on the same nails and discovered that the grouting pressure and the overburden pressure parameters were effective on the pull-out resistance [31].

Hong et al., in a study, stated that the frictional strength mobilized at the interface of nail and the surrounding soil depends on factors such as saturation percentage (degree of saturation), water content, dilatation, grouting under pressure due to soil layer weight, grouting pressure, etc. The researchers stated that the friction created by the roughness between the surface of the nail and the soil is an important and critical factor which is hardly controlled both in the laboratory and in the field because of technical problems. The researchers used threaded plastic nails to achieve their goals and showed that dilatation was an important determinant in the nail pull-out resistance. They also concluded that the peak pull-out resistance increased almost linearly with growing angles of the threads created on the nails. Moreover, the values of pull-out resistance diminished with an increase in the pull-out displacement following the peak pull-out resistance linearly [11].

Rawat and Gupta conducted a study examining the effect of nail shape on pull-out resistance. In their research, they tested different types of nail with different shapes and added some parts to the nails. The researchers found that adding the parts increased the magnitude of pull-out force, which was greater in circular ones (circular discs) [24].

Since the soil mass and nail have various properties, the stresses caused by the excavation progress in the soil lead to strain differences between the nail and the surrounding soil. This creates limitations for the soil particles around the nails. Due to the fact that the frictional force at the soil-nail interface is a transient mechanism between the two materials, the confinement effect of the nail surface is reduced to a limited distance in the soil mass.

In execution projects, the nails are grouped together and close to the soil. If the nails are close together, the affected area (radius of efficacy) of a nail may overlap with the area affected by the neighboring nail. Therefore, the interactions between the nails in the nail group in the reinforced soil are important.

In a study analyzing upper bound finite element, Jagdish and Jyant investigated the horizontal pull-out capacity of the two vertical strip anchors placed along the same vertical plane in sandy soil. The researchers measured the efficiency of the group by altering the distance between the anchors and for different values of the embedment ratio (H/B), the internal friction angle of the soil, and the friction angle of the soil-anchor interface. They obtained the optimum distance between the end plates of the anchors relative to the width of these plates (Sopt/B) within the range of 0.5 to 1.4. The researchers observed that the maximum pull-out resistance of the group under identical H/B conditions was nearly 1.01-1.25 times the pull-out resistant of the group with S/B=0 [14].

In this study, several tests were designed to investigate the effect of parameters such as the nail length to diameter ratio, the distance between nails and nail surface roughness on the efficiency of the nail group on pull-out resistance. This set of tests is performed on single and double nails.

2. Pull-out Resistance

Since part of the tensile forces in soil nailing is caused by shear stresses distributed at the interface between the soil and nail; therefore, resistance of the soil-nail interface is a key parameter used to control the deformation, pattern and stability evaluation of soil nailing structure. Figure 1 displays the ideal state of the soil-nail interface.

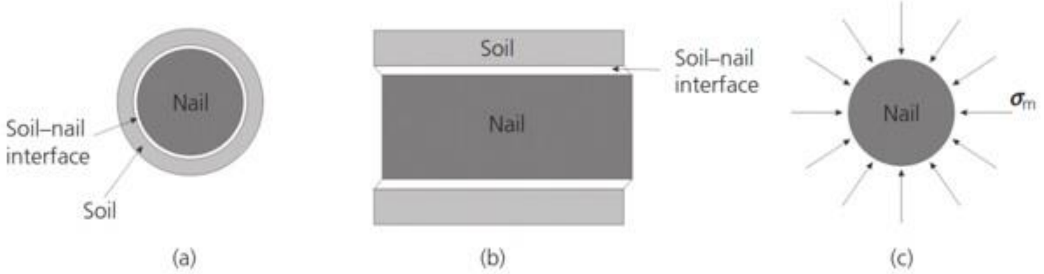


Fig. 1. Grouted nail system idealization: (a) Idealized system; (b) Displacement of relative shear; and (c) Effective confining stress [8].

Various researchers have performed various laboratory tests in the field of pull-out in order to study the soil-nail interface resistance. The researchers concluded that soil-nail pull-out resistance depends on various parameters such as soil shear strength, dilatation, grouting pressure, nail installation method, stress release during drilling, etc. [1, 6, 15, 16, 18, 21, 27, 28, and 32]. Guilioux and Schlosser proposed the following equation for calculating the final nail pull-out resistance [7]:

$$\tau_f = Pc' + 2D_e\sigma_v'\mu^* \qquad (1)$$

Where, the perimeter of the nail is P, c′ represents the effective soil cohesion, De is equivalent to the flat reinforced bar width, σ_v' denotes the vertical stress at the reinforcement mean depth, and μ^* is the apparent coefficient of friction resulting from the maximum shear stress division by vertical stress. When applying this equation, the final pull-out resistance is not dependent on the confining stress (σ_m in Fig 1 c). Figure 2 shows a schematic diagram of how to extract the nail from the soil.

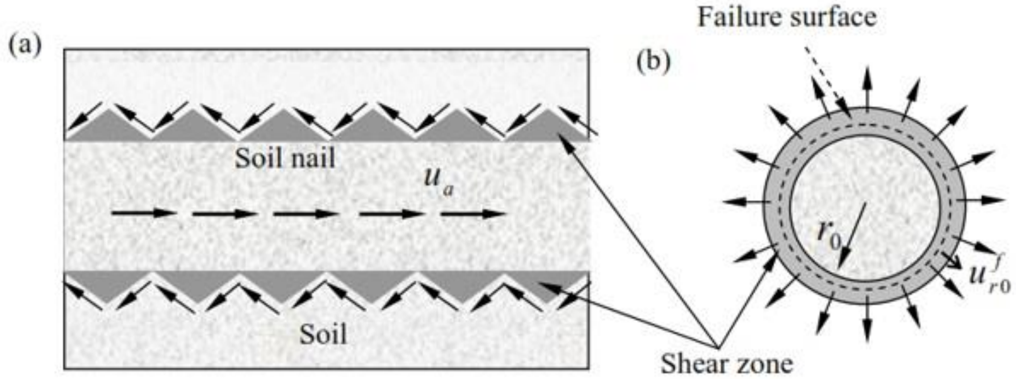


Fig. 2. An idealized pullout interaction between soil and soil nail schematic view (a) the view in axial direction and (b) cross sectional view [10].

3. Laboratory equipment

Figure 3 shows an overview of the pull-out device manufactured at Tabriz University. The device is made up of three main parts: a large box measuring 120 * 100 * 140 cm (length * width * height) containing soil and nail, a 150 * 180 cm Portal Frame coiled box used to apply surcharge and pull-out system equipment.

Fig. 3. The test apparatus.

3.1 Test box

The box was made of 10 mm thickness steel sheet whose hardness was high enough to withstand vertical loading up to about 180 kPa. A groove was created on the front wall of the box, where the nails were inserted through the groove into the soil and finally pulled out. In order to avoid the box boundaries effect on the results of the pull-out test, the distance between the first nail and the box wall should be controlled. This distance was estimated at least 10 times the diameter of the nail, according to numerical studies. However, Hsu and Liao (1998) considered the area influenced by the boundaries for vertical cylindrical anchors and piles 2 to 5 times their diameter from the center.

The foundation of the device consisted of two parallel profiles of 150 cm in length and the whole system of the pull-out box, jack, gauges, and necessary ties were designed and implemented on its rigid foundation to prevent box slip and displacement. The box was also made of 10 mm thickness sheets. The entire set was mounted on a 10 mm thick plate attached to the foundation of the device itself. One side of the box was made of Perspex glass sheet to be used in future studies and in order to observe the deformation and deposition of the soil sample.

3.2 Apply overburden pressure

In this study, an electric motor and a hydraulic jack mounted on a rigid steel plate above the soil were used to apply the overburden pressure. The capacity and motor course of this jack were 300 kN and 150 mm, respectively. This jack was installed on a frame at the desired distance from the box (Fig. 3). The upper steel plate to which the surcharge was applied was 25 mm thick and its hardness increased by a series of hardeners (steel pieces). The amount of the applied vertical load was measured by a data logger indicating the maximum applied force and stress. The upper plate settlement during the apply surcharge was measured by LVDTs installed on this plate.

3.3 Pull-out equipment

An electric motor and a hydraulic jack with a capacity of 250 kN and a displacement rate of 1-1.5 mm/min were used to pull-out the nails. This jack was aligned along the length of the nails and was attached to the frame using hard steel elements. A 50 kN load cell was mounted between the hydraulic jack and the nail to measure the pull-out force. The nail displacement was also measured using an LVDT (Fig. 3).

3.4 Sand

The required materials in this test set included sandy soil with the grain size distribution being illustrated in Fig. 4. This soil was used in a completely dry state and its maximum dry density was based on standard proctor compaction test of 1630 kg/m³ whose optimum moisture content ranged between 19 and 21%. The main parameters of this soil are presented in Table 1.

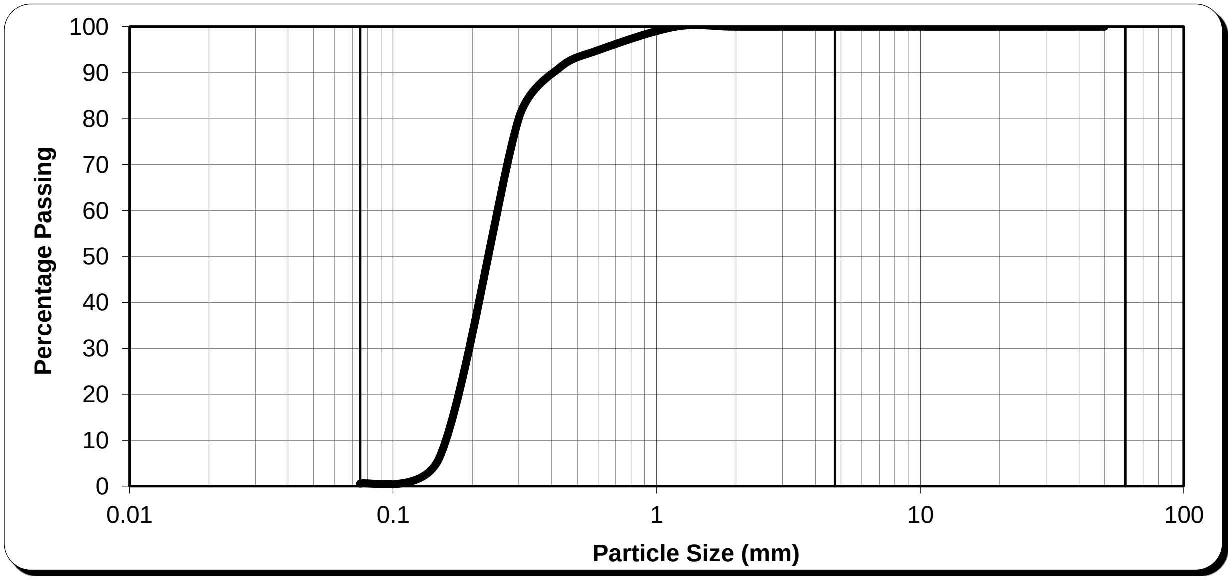


Fig. 4. Distribution curve of particle size.

Table 1. The soil physical properties.

Gravel (%)	0
Sand (%)	98
Silt (%)	2
Clay (%)	0
D_{10} (mm)	0.157
D_{30} (mm)	0.189
D_{50} (mm)	0.228
D_{60} (mm)	0.251
C_u (D_{60}/D_{10})	1.598
C_C ($D_{30}^2/D_{10}*D_{60}$)	0.906
Maximum dry density (kg/m^3)	1630
Optimum moisture content (%)	19-21

The classical Mohr-Columb equation was applied to specify the parameters of the soil strength:

$$\tau_f = C + \sigma_n tan\emptyset \quad (2)$$

In this equation, τ_f represents the maximum soil shear stress, the soil cohesion parameter is C, σ_n denotes the normal stress at the shear plane, and ϕ shows the angle of the internal friction at the shear plane. Considering the overburden and shear failure forces and in order to calculate values of C and ϕ, the above equation and the direct shear device were used. The results of this test are presented in Fig. 5.

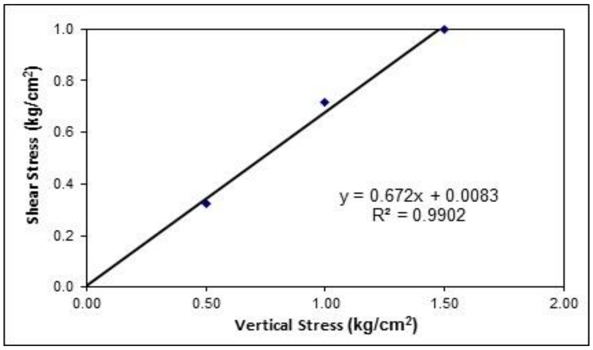


Fig 5. Coulomb failure line for used soil.

The equation y= 0.672x + 0.01 is given by Columb failure equation for this soil which is obtained by solving this equation C = 1 kPa and ϕ = 34 degrees. In general, this soil is one of the poorly graded soils (SP).

3.5 Nail

We used three types of smooth, ribbed, and threaded bar in order to perform the tests (Fig. 6). The smooth bar had a diameter of 10 mm. the ribbed and threaded bar had an external diameter of 10 mm and internal diameter of 8.8 mm and 8.32 mm, respectively. The thread depths in ribbed and threaded bar were 0.6 and 0.84 mm, respectively. The magnitude of surface roughness of the bar, which plays a key role in causing friction at the interface of the soil and bar, is determined, using the parameter of the coefficient of roughness, by the following equation:

$$R = \left(\frac{T_d}{D_{in}}\right)\left(\frac{1}{S_P}\right)\left(\frac{T_d}{D_{50}}\right) \quad (3)$$

Where, T_d represents the depth of bar threads, D_{in} shows the bar internal diameter equal to external diameter of bar minus twice the depth of threads, S_P indicates bar pitch threads, and D_{50} is the mean soil particle size.

In this equation, T_d/D_{in} represents the relative roughness of the surface of a rough nail, 1/SP is the amount of roughness per unit length, and T_d/D_{50} shows the relative roughness of the surface of the nail relative to the size of the soil particles. The coefficient of roughness for threaded rods with depths of 0.6 and 0.84 mm were calculated as 0.045 and 0.489, respectively. Therefore, the coefficient of roughness of the threaded bar was approximately 10 times that of the ribbed bar. The coefficient of roughness of the smooth bar was set to zero.

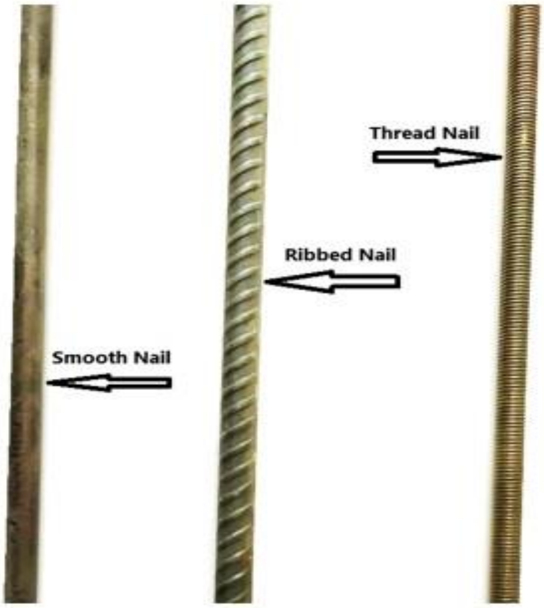


Fig. 6. Types of nails used.

4. Instrumentation and measurements

To implement the pull-out tests, comprehensive instrumentation was used in laboratory. The used transducers and measurements are presented as follows:

4.1 Overburden pressure measurement

The overburden pressure was applied by hydraulic jack which is located on the top of the box in the pull-out tests done in laboratory. A pressure gauge was fixed on the top cover to measure the applied pressure.

4.2 Axial strain of the soil nail measurement

We adhered two strain gauges to the steel bar having 40 cm spacing and used these types of strain gauges in order to estimate the axial strain of the soil nail. The data can be utilized to gain the frictional shear force distribution on the soil nail surface (Fig. 7).

4.3 The pull-out displacement of the soil nail measurement

A linear variable differential transformer (LVDT), as presented in Fig. 7, was installed at the nail head to evaluate the pull-out displacement.

4.4 The pull-out force measurement

A local cell was used to measure the pull-out force. This cell is placed between the pull-out reaction frame and the hydraulic jack, as illustrated in Fig. 7.

A five-channel data logger which is connected to a computer is used to read all transducers, automatically.

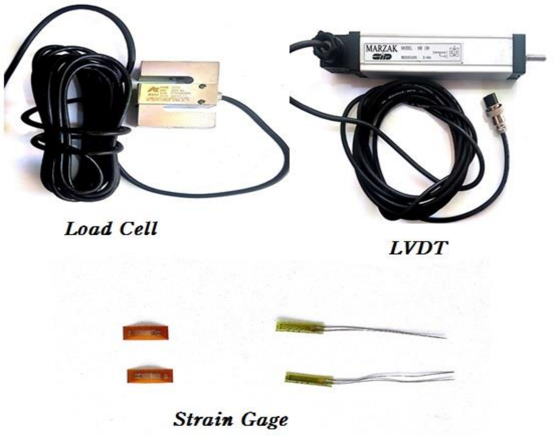


Fig. 7. Transducers were used.

5. Experimental process

In the field, we usually used the nail with a diameter of 100 mm and a length to diameter ratio of 25 to 50 with a pull-out rate of about 1 mm/min. Elias and Juran suggested that, in order to perform the pull-out tests in the field, the grouted nail of 250 cm length should be used under load-controlled conditions [3].

In the laboratory, sandy soil was poured in the box into 14 layers (each layer 10 cm in thickness) and, then, compacted. The weight of the soil mass needed for each layer was calculated as 10 cm in thickness to reach the required density and, then, poured into the box by throwing, until it reached a density of about 80% and, finally, compacted manually. When filling the box with soil, the steel nails in the given alignment were mounted horizontally within the box to prevent stress changes in the soil poured during the installation of the nails. Once the nail was inserted and the box was completely filled with soil, a 2.5 cm thick steel plate was put on the soil to apply and distribute the surcharge. The surcharge was then applied to the sample by a loading hydraulic jack. The needed surcharge was applied to the sample at least 48 hours before the test to perform the pull-out test under stable stress conditions. The rate of the pull-out in these tests ranged from 1 to 1.5 mm/min with the pull-out force, displacement and reading of other sensors being recorded using a data logger. Moreover, the required diagrams were plotted by computer programs.

The pull-out tests were performed in various parts. In the first part of the tests, three smooth, ribbed, and threaded bars of 1 m in length and 10 mm in external diameter with 83 kPa surcharge were tested, separately. In the second part of the tests, rods with different length to diameter ratios and fixed surcharge were tested by selecting a specific coefficient of roughness. In the third part, the bars were tested in double nails with different intervals (the distance between the bars is a function of the diameter of the bars).

5.1 Part 1: Using the nail with a constant length and various surface roughness

In this part, the pull-out tests were done using a fixed length single nail and different surface roughnesses. The surcharge on top of the sandy soil was equal to 83 kPa. One of the factors affecting the magnitude of the pull-out force is the apparent friction coefficient calculated by the following equation:

$$f = \frac{\tau_{max}}{\sigma_n} \tag{4}$$

Where, τ_{max} is the maximum shear stress which is calculated from the following equation:

$$\tau_{max} = \frac{P}{\pi DL} \tag{5}$$

Where P denotes the maximum pull-out force, the nail diameter is shown by D, and L shows the nail length.

σ_n indicates the mean of the horizontal and vertical stresses on the nail surface obtained from the following equation:

$$\sigma_n = \frac{\sigma_v + \sigma_h}{2} = \frac{(1 + k_0)}{2}\sigma_v \tag{6}$$

σ_v represents the vertical stress on the nail, σ_h denotes the horizontal stress on the nail, k_0 represents the earth pressure coefficient at rest (k_0=1-sin ϕ), and ϕ is the soil internal friction angle.

In this part, the results of the test show that the pull-out force went up with enhancing the nail surface roughness. In the smooth nail, the highest pull-out force occurred in a small displacement, while in the ribbed and rough nails, this occurred in larger displacements (Fig. 8). The diagram of smooth nail behavior was similar to an elastic-plastic behavior for the pull-out. Figs. 9 and 10 illustrate the relationship between the maximum shear stress (calculated by equation 5) and the coefficient of roughness plus the apparent friction coefficient. As shown in these figures, it is evident that with increasing the nail coefficient of roughness and the apparent coefficient of friction, the maximum shear stress required for the nail pull-out also increased.

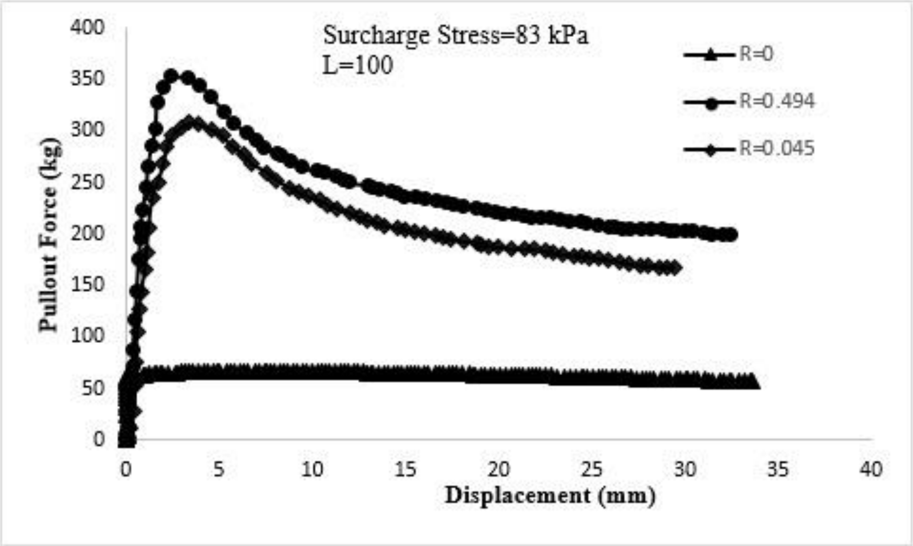


Fig. 8. Pullout force versus displacement for different surface roughness factors.

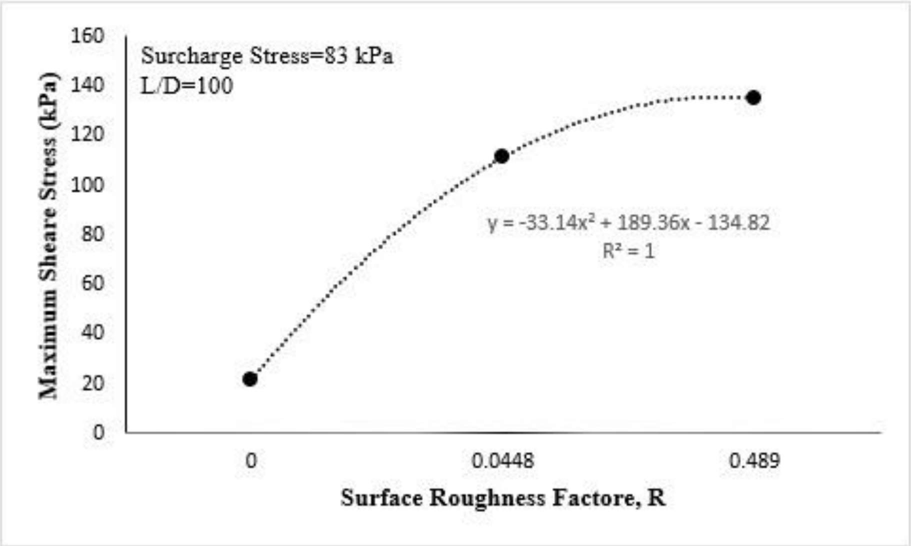


Fig. 9. Relation between maximum shear stress and surface roughness factor.

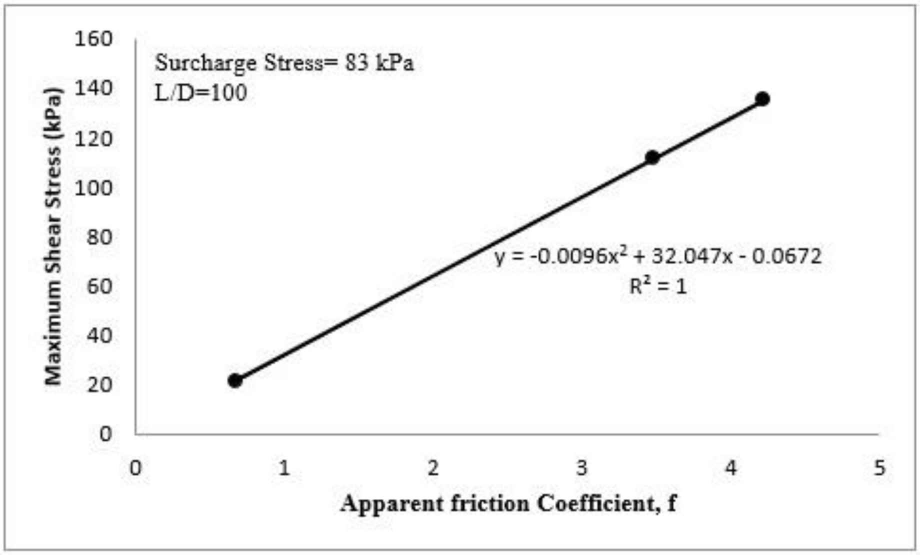
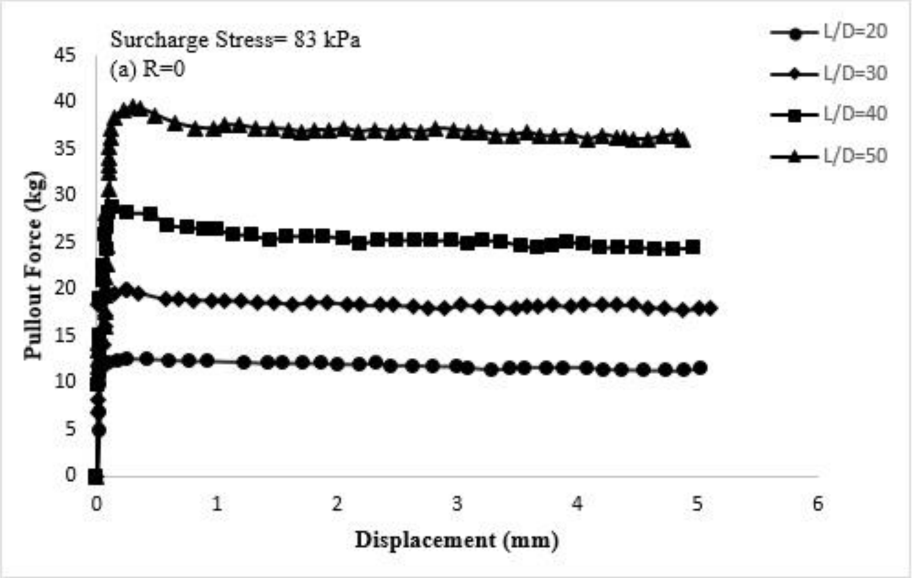


Fig. 10. Relation between maximum shear stress and apparent friction coefficient.

5.2 Part 2: Utilizing a single nail with different length to diameters ratios

In the second part of the tests, we selected a single nail with a smooth surface and a single nail with a coefficient of roughness R = 0.489 (corresponding to threaded nail). We tested the nail with different length to diameter ratios (L/D) of 20, 30, 40 and 50 under 83 kPa surcharge. The nail-buried length was gradually diminished during the pull-out test. The pull-out force per unit length was obtained by pull-out force measurement and the buried length. The pull-out force-displacement diagram is demonstrated in Fig. 11. The result shows that, for the rough nail, a larger length to diameter ratio caused development of peak stresses at larger displacements. Note that all the pull-out force-displacement curves have a definite peak value, followed by a reduction in the pull-out force value, mainly due to the reduction in normal stress applied to the nail. Fig. 12 reveals the diagram of the peak pull-out force versus the length to diameter ratio. In this figure, it is also apparent that as the length to diameter ratio increased, so did the value of peak pull-out force. Moreover, for both types of nails, the peak pull-out force behavior was linearly relative to the length to diameter ratio.



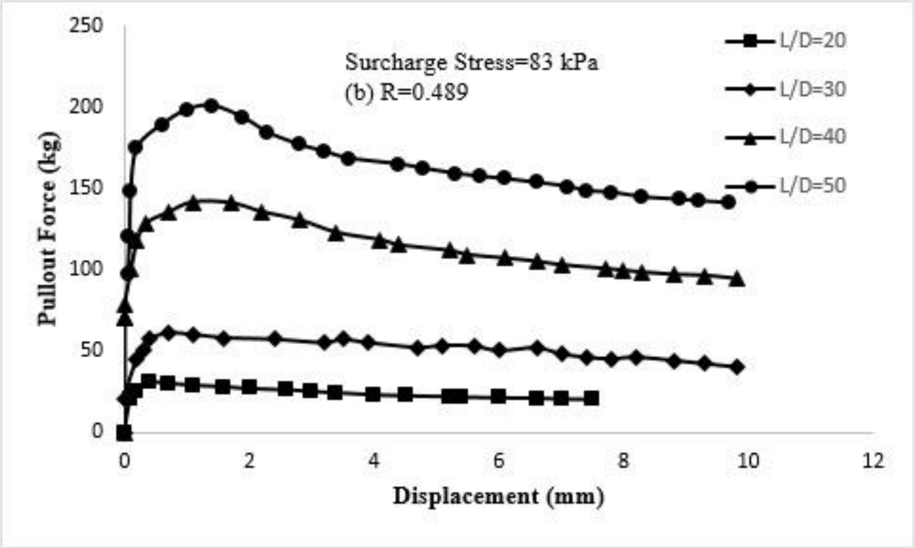


Fig. 11. Pull-out force versus displacement of single nail with different aspect ratios (a) R=0 (b) R=0.489.

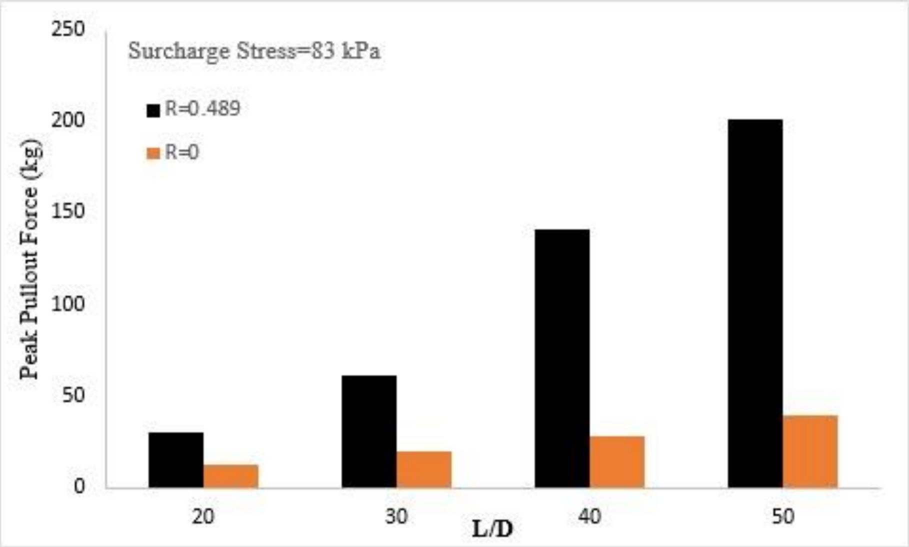


Fig. 12. Peak pullout force versus length to diameter ratio of single nail.

5.3 Part 3: Using double nails

Since, in practical applications, the nails are grouped and used together; in this part, we used two nails with the same surface roughness coefficient, which were horizontal and parallel to each other and, at different distances (the distance is a function of the diameter of the nail), adjacent to each other. The main purpose of this part was to study the efficiency of the nail group when pulled together. The efficiency of the nail group was expressed as the ratio of the mean pull-out force obtained from the pull-out test of double nails to the value obtained from the pull-out test of a single nail. In order to find the optimal distance between the two nails where the efficiency of the group reaches 100%, the tensile test was performed at different distances as summarized in Fig. 13. In this figure, a diagram of the pull-out force versus displacement – in case of using smooth and rough nails – is presented in the nail group. The results indicated that, under the same displacement conditions, as the distance between the two nails increased, so did the pull-out force. This increase in the pull-out force was greater until the two nails were separated, which corresponded to the surface roughness of the nail, after which this pull-out force diminished under the same displacement conditions.

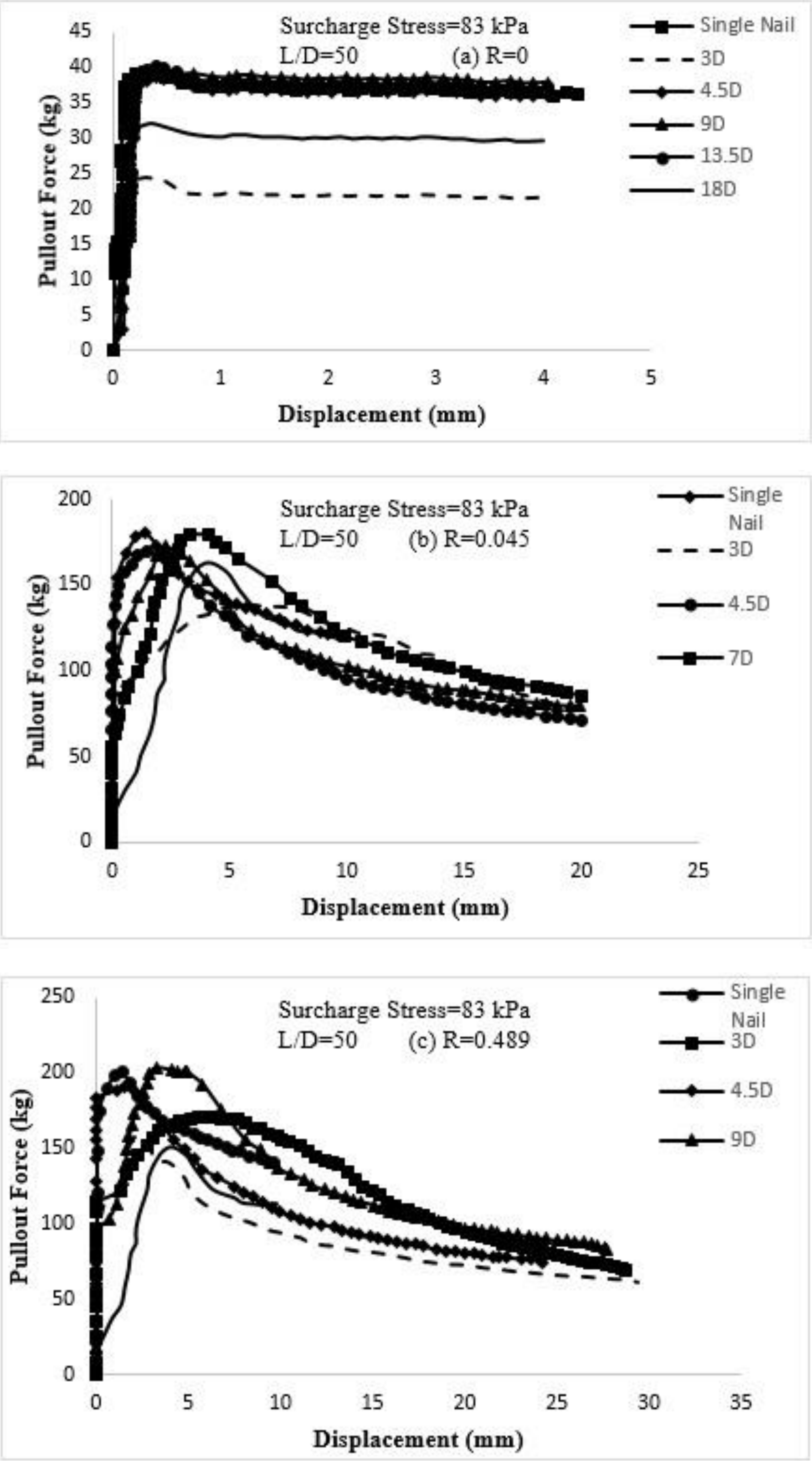


Fig. 13. Pullout force versus displacement of double-nail tests (a) R=0, (b) R=0.045, (c) R=0.489.

Note that the 100% efficiency of the nail group was dependent on the nail surface roughness. Besides, for the nail with different surface roughness values, the efficiency was obtained at different distances between the nails. In the tests performed in this study, which are presented in Fig. 14, it was found out that an almost linear relationship existed between the increase in the efficiency of the group and elevation of the ratio of the distance between two nails to the diameter of nail (S/D). The nails with a length to diameter ratio (L/D) of 50, with surface roughness coefficients of zero, 0.045 and 0.489, offered almost 100% efficiency at S / D ratios of 5.5, 7, and 8.5, respectively. Fig. 15 also displays the relationship between the coefficient of roughness and S/D ratio. This figure represents the lowest S/D ratio required to achieve 100% efficiency in a paired nail group with a specified surface roughness coefficient.

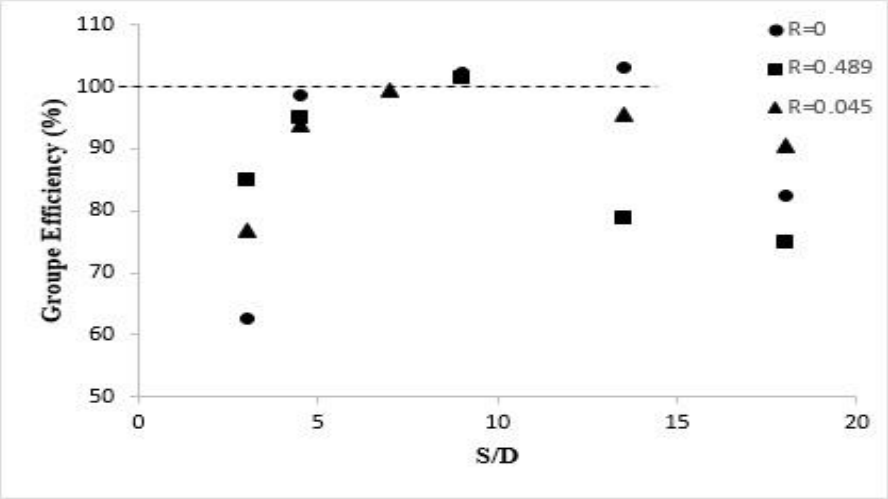


Fig. 14. Relation between group efficiency and spacing to diameter ratio.

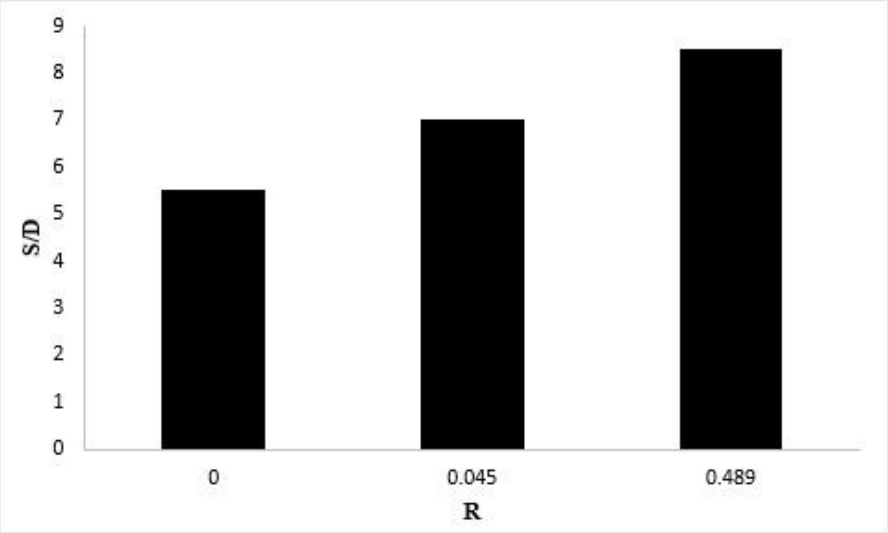


Fig. 15. Relationship between the coefficient of roughness and S/D ratio.

6. Conclusion

In this study, the pull-out resistance of the nail group was investigated to determine the effect of the distance between nails in order to determine the nail group efficiency in sandy soil. In the conducted tests, using the displacement rate control method, the soil-nail pull-out capacity was measured for single and double nails at different distances. In order to consider the effect of nail surface roughness, we used the parameter of the nail surface roughness coefficient (R) which is itself dependent on parameters such as the depth of thread on the nail, the number of threads per unit length, soil particle size, etc.

In the performed tests, it was observed that the efficiency in the paired nail group was strongly dependent on the surface roughness coefficient of the nail, and the minimum distance required to reach the maximum efficiency was a function of this factor. In these tests, a significant reduction was found in the pull-out capacity and, thus, a significant reduction was found in the efficiency of the nail group where the distance between nails was 3 times the diameter of the nail. This was mainly due to the interaction between neighboring nails causing interference with soil stresses (stress interference). The best distance between two nails to achieve the maximum efficiency was 5 to 10 times the nail diameter, depending on the roughness of the nail surface.

In all tests, the pull-out force curve of the nail group vs displacement was similar to that in the single-nail curve with a peak value. Afterwards, a sharp reduction occurred in the magnitude of the pull-out force again due to a reduction in the normal stress applied to the nails. This pull-out force was mainly mobilized within the first few millimeters of the nail displacement.

Data availability

Submitted article contains all data, methods, models, and codes generated or used during the study.

REFERENCES

[1] Cartier, G., and Gigan, J.P. (1983). “Experiments and observations on soil nailing structures.” In Improvement of Ground: Proceedings of the 8th European Conference on Soil Mechanics and Foundation Engineering, Helsinki, Finland, pp. 473-476.

[2] Chu, L.M., and Yin, J.H. (2005). “Comparison of interface shear strength of soil nails measured by both direct shear box tests and pull-out tests.” ASCE Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol.131, pp. 1097-1107, DOI: 10.1061/ (ASCE) 1090-0241(2005)131:9(1097).

[3] Elias, V., and Juran, I. (1991). “Soil nailing for stabilization of highway slopes and excavations.” Federal Highway Administration Report Ref FHWA-RD-89-198, Washington DC, USA.

[4] Farokhzad, F., Shabani, M.J., and Hasanpou, A. (2020). “Investigating Stabilized Excavations Using Soil Nailing Method in Urban Context.” Journal of Rehabilitation in Civil Engineering 8-2 (2020) 126-138 DOI: 10.22075/JRCE.2019.10841.1175.

[5] FHWA-NHI-14-007. (2015). "GEOTECHNICAL ENGINEERING CIRCULAR" NO. 7 SOIL NAIL WALLS - REFERENCE MANUAL. National Highway Institute U.S. Department of Transportation Federal Highway Administration, Washington, DC 20590.

[6] Franzen, G. (1998). "Soil Nailing - A Laboratory and Field Study of Pull-out Capacity." Ph.D. Thesis, Chalmers University of Technology, Goteborg, Sweden.

[7] Guilloux, A., and Schlosser, F. (1982). "Soil nailing: practical applications in recent development in ground improvement techniques." Proceedings of the International Symp. Asian Institute of Technology, Bangkok, Thailand, pp. 389-397.

[8] Hajialilue-Bonab, M., and Razavi, S.K. (2015). "A study of soil-nailed wall behaviour at limit states." Ground Improvement, 169 (1), pp. 64-76, DOI: 10.1680/grim.14.00021.

[9] Hong, C.Y., Liu, Y.F., Zhang, M.X., and Borana, L. (2017). "Influence of Critical Parameters on the Peak Pull-out Resistance of Soil Nails under Different Testing Conditions." International Journal of Geosynthetics and Ground Engineering, 3:19, pp. 3-17, DOI: 10.1007/s40891-017-0095-5.

[10] Hong, C.Y. (2011). "Study on the Pull-out Resistance of Cement Grouted Soil Nails." Ph.D. Thesis, the Hong Kong Polytechnic University, Hong Kong.

[11] Hong, C.Y., Zhang, Y.F., Guo, J.W., and Li, G.Y. (2015). "Experimental Study on the Influence of Drill hole Roughness on the Pullout Resistance of Model Soil Nails." International Journal of Geomechanics, DOI: 10.1061/ (ASCE) GM.1943-5622.0000491

[12] Hong, C.Y., Yin, J.H., and Pei, H.F. (2013). "Comparative study on pullout behavior of pressure grouted soil nails from field and laboratory tests." J Central South University; 20:2285–92, DOI: 10.1007/s11771-013-1735-0.

[13] Hsu, S.T., and Liao, H.J. (1998) "Uplift behavior of cylindrical anchors in sand." Canadian Geotechnical Journal, 35: 70–80, DOI: 10.1139/cgj-35-1-70.

[14] Jagdish, P.S., and Jyant, K. (2013). "Horizontal Pullout Resistance of a Group of Two Vertical Anchors in Sand." KSCE Journal of Civil Engineering. 17(7):1614-1620, DOI: 10.1007/s12205-013-0372-3.

[15] Jewell, R.A., and Pedley, M. (1990). "Analysis for Soil Reinforcement with Bending Stiffness." Journal of Geotechnical Engineering, 118(10).

[16] Jewell, R.A., and Pedley, M. (1990). "Soil Nailing Design." Journal of Ground Engineering, 23(2): 30-36.

[17] Junaideen, S.M., Tham, L.G., Law, K.T., Lee, C.F. and Yue, Z.Q. (2004). "Laboratory study of soil-nail interaction in loose, completely decomposed granite." Canadian Geotechnical Journal. 41: 274-286, DOI: org/10.1139/t03-094.

[18] Lou, S.Q., Tan, S.A. and Yang, K.Y. (2000). "Pull-out resistance mechanism of a soil nail reinforcement in dilative soils." Soils and Foundations 40(1):47–56, DOI: org/10.3208/sandf.40.47.

[19] Milligan, G.W., and Tei, K. (1998). "The pull-out resistance of model soil nails." Soils and Foundations, 38(2): 179-190, DOI: 10.3208/sandf.38.2-179.

[20] Pedley, M. (1990). "The Performance of Soil Reinforcement in Bending and Shear." Ph.D. Thesis, Wolfsan College, University of Oxford.

[21] Pei, H., Yin, J., Zhu, H., and Hong, C.Y. (2013). "Performance monitoring of a glass fiber-reinforced polymer bar soil nail during laboratory pull-out test using FBG sensing technology." International Journal of Geomechanics, 13(4), pp. 467–472, DOI: 10.1061/ (ASCE) GM.1943-5622.0000226.

[22] Pradhan, B. (2003). "Study of pull-out behavior of soil nails in completely decomposed granite fill." Ph.D. thesis, Department of Civil Engineering, The University of Hong Kong, Pok Fu Lam.

[23] Raju, G.V.R. (1996). "Behavior of nailed soil retaining structures." Ph.D. thesis, Nanyang Technological University, Singapore.

[24] Rawat, S., Gupta, A.K. (2017). "Numerical modelling of pull-out of helical soil nail." Journal of Rock Mechanics and Geotechnical Engineering, 9(4), pp. 648-658, DOI: 10.1016/j.jrmge.2017.01.007.

[25] Schlosser, F. (1991). "The multi criteria theory in soil nailing." Ground Engineering 24(9):30–39.

[26] Schlosser, F. (Editor) (1993). "Recommendations Clouterre 1991-soil nailing recommendations 1991. Presses de l'Ecole Nationale des Ponts et Chaussees, Paris." [English translation NTIS No. PB94-109980, U.S. Federal Highway Administration, Washington, D.C.]

[27] Su, L.J. (2006). "Laboratory pull-out testing study on soil nails in compacted completely decomposed granite fill." PhD Thesis, Hong Kong Polytechnic University.

[28] Su, L.J., Yin, J.H., and Zhou, W.H. (2010). "Influences of overburden pressure and soil dilation on soil nail pull-out resistance." Journal of Computers and Geotechnics, 37(4), pp. 555–564, DOI: 10.1016/j.compgeo.2010.03.004.

[29] Tokhi, H., Ren, G., and Li, J. (2016). "Laboratory study of a new screw nail and its interaction in sand Laboratory study of a new screw nail and its interaction in sand." Journal of Computers and Geotechnics, 78, pp. 144-154, DOI: 10.1016/j.compgeo.2016.05.009.

[30] Wan-Huan, Z., and Jian-Hua, Y. (2008). "A simple mathematical model for soil nail and soil interaction analysis." Journal of Computers and Geotechnics, 35 (3), pp. 479–488, DOI: 10.1016/j.compgeo.2007.07.001.

[31] Yin, J., and Zhou, W., (2009). "Influence of grouting pressure and overburden stress on the interface resistance of a soil nail." Journal of Geotechnical and Geoenvironmental Engineering, 135 (9):1198–208, DOI: org/10.1061/ (ASCE) GT.1943-5606.0000045.

[32] Zhang, L.L., Zhang, L.M., and Tang, W.H. (2009). "Uncertainties of Field Pull-out Resistance of Soil Nails." Journal of Geotechnical and Geoenvironmental

Engineering, 135 (7), pp. 966-972, DOI: 10.1061/ (ASCE) GT.1943-5606.0000014.

[33] Zhang, G., Jie, C., and Liping, W. (2014). "Failure Behavior and Mechanism of Slopes Reinforced Using Soil Nail Wall under Various Loading Conditions." Soils and Foundations, vol. 54, no. 6, Elsevier, 2014, pp. 1175–87, doi:10.1016/j.sandf.2014.11.011.

[34] Zi-Hang, D., Wei-Dong, G., Gui-Xin, Z., Yu, O., and Yan-Jia, C. (2016). "Moso Bamboo Soil-Nailed Wall and Its 3D Nonlinear Numerical Analysis." International Journal of Geomechanics, 16(5):04016012, DOI: 10.1061/ (ASCE) GM.1943-5622.0000634.