Pullout resistance of a soil nail in a completely decomposed granite soil under different overburden stresses and grouting pressures

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ABSTRACT
The present study focuses on the pullout resistance of grouted soil nails which are commonly used in Hong Kong. Data from a series of laboratory and field pullout tests are presented for investigation of key influencing factors on the fundamental interaction mechanism of soil nail pullout resistance. Laboratory soil nail pullout tests were carried out on a completely decomposed granite (CDG) soil in a nearly saturated condition under a combination of different grouting pressures and overburden stresses. In addition, a total of 8 pullout tests were conducted in a slope site with different overburden stresses and grouting pressures. The study shows that the grouting pressure and overburden stress have interactional influence on the soil nail pullout resistance. New understandings and findings from the study are presented.

RÉSUMÉ
La présente étude met l'accent sur la résistance retrait de clous sol injecté qui sont communément utilisés à Hong Kong. Une série d'essais d'arrachement et examens de laboratoire décrochage sur le terrain sont présentés pour l'étude des facteurs influençant clés sur le mécanisme fondamental de l'interaction arrachement dans le sol à ongles. Les tests de laboratoire des sols à ongles retrait ont été effectués sur un granite complètement décomposé (CDG) du sol dans un état proche de la saturation en vertu d'une combinaison de différentes pressions d 'injection et les morts de stress. En outre, un total de tests 8 arrachement ont été réalisés dans un site de pente avec des morts-terrains différents stress et de pressions d 'injection. L'étude montre que l'injection sous pression et le stress des morts-terrains ont une influence sur l'interaction arrachement dans le sol à ongles. De nouvelles compréhensions et les conclusions de l'étude sont présentés.

1 INTRODUCTION

Grouted soil nails have been widely used in slope stabilization projects. In Hong Kong, more than 200 slopes and retaining walls are upgraded using grouted soil nails each year (GEO 2008). The main advantages of the soil nailing technique are (a) short construction period, (b) utilization of small construction equipment, and (c) low cost. In the design of a soil nailed slope, the pullout resistance of a soil nail is a key parameter. However, the influence of both grouting pressure and overburden stress on the soil nail pullout interface shear resistance is still not well understood due to the complex of soil-grout interactions.

Laboratory pullout tests are economic and effective for investigating the interaction mechanism between soil and soil nail under controlled conditions (Franzen 1998; Hong *et al*. 2003; Milligan *et al*. 1997; Pradhan *et al*, 2006; Su 2006; Yin and Su 2006; Zhou 2008). In comparison with laboratory pullout testing, the field pullout testing is more related to the field performance of a soil nail, and better accounts for the effects of different influencing parameters, so that the captured correlation between the pullout resistance and certain parameters is more realistic. To date, there is a lack of a systematic investigation on the field pullout response of soil nails constructed under different overburden pressures (soil depths) or grouting pressures. Yeung *et al*. (2007) reported that the grouting pressure increases the bond strength of the soil-cement grout interface on the basis of a full scale field evaluation. But the study was only limited to the pullout investigation of grouted glass fiber soil reinforcement in ground, and the effect of grouting pressure on the pullout resistance was not quantified.

The present study focuses on the grouted nails which are commonly used in Hong Kong. A grouted soil nail is normally constructed by placing a steel bar in the middle of a drillhole in a slope and then grouted by cement slurry. Data from a series of laboratory pullout tests and field pullout tests are presented for investigation of key influencing factors on the fundamental interaction mechanism of soil nail pullout resistance. Laboratory soil nail pullout tests were carried out on a completely decomposed granite (CDG) soil in a nearly saturated condition under a combination of different grouting pressures and overburden stresses. In addition, a total of 8 pullout tests were conducted in a slope site with different overburden stresses and grouting pressures. Typical test data are presented, explained, and discussed in this paper. The study shows that the grouting pressure and overburden stress have interactional influence on the soil nail pullout resistance. Field pullout tests on pressure grouted soil nails show that the pullout shear stress of soil nails appears to increase with both the grouting pressure and overburden stress.

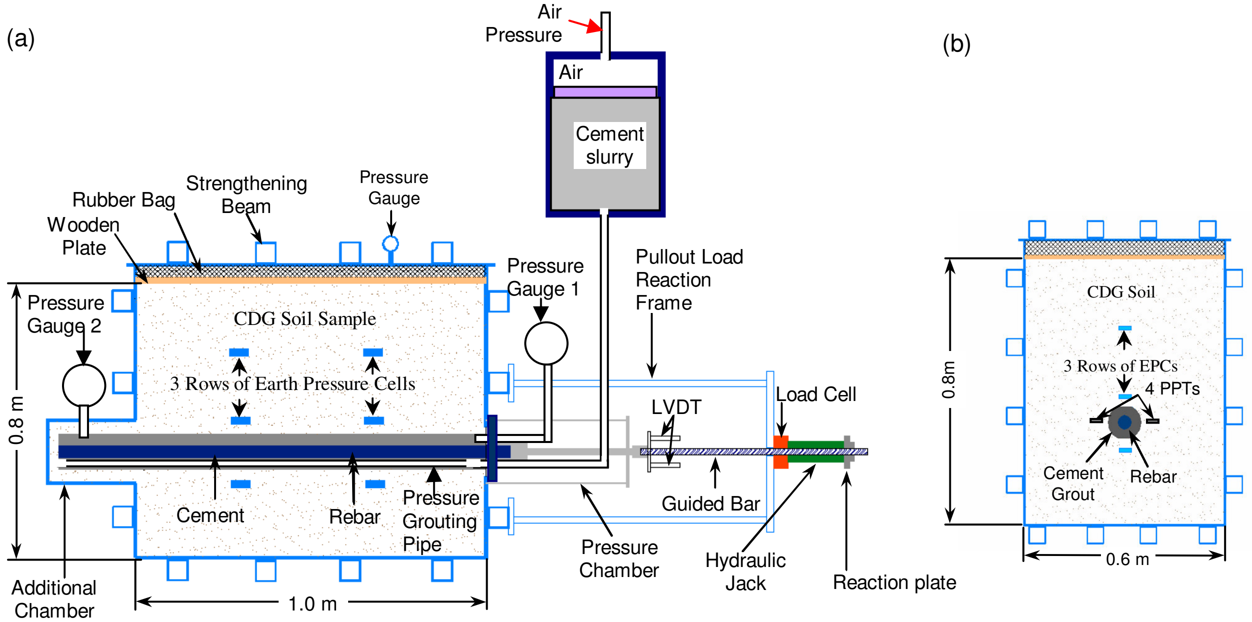


Figure 1. Set-up of the soil nail laboratory pullout test with full instrumentation and grouting and saturation devices (a) longitudinal section along soil nail, and (b) cross-section of the soil nail.

2 LABORATORY PULLOUT TEST SETUP AND MATERIALS PROPERTIES

The pullout box designed by Yin and Su (2006) has been used in the present study. The internal dimensions of the box are 1000 mm long, 600 mm wide and 830 mm high as shown in Figure 1. This pullout box has a few special components which were designed for special purposes:

(a) To simulate the overburden stress in a slope, an overburden stress application device is placed on the top cover of the box, where a rubber bag filled with de-aired water is attached to apply the vertical pressure on the top surface of the soil in the box.

(b) To make the soil stresses on the soil nail inside the box more uniform during the soil nail pullout, an additional chamber on the left side of the box (Figure 1) is used to cover the end of the soil nail.

(c) To apply back water pressure for soil saturation, a special waterproof pressure chamber is fixed at the nail head.

(d) To conduct pressure grouting of the cement slurry, a grouting system is designed to control and monitor the ingoing and outgoing grouting pressure.

(e) To apply a pullout force at the nail head, a pullout device with a special reaction frame with alignment design is used.

In addition, the pullout box is instrumented with six earth pressure cells, four pore water pressures transducers (PPT), two LVDTs (Linear Variation Displacement Transformer), one load cell, one water pressure gauge, and two grouting pressure gauges (one at nail head and one at nail end) as shown in Figure 1. More details on the box design and setup can be found in Yin and Su (2006) and Yin *et al.* (2009).

The test procedures include box preparation, soil compaction, application of the overburden stress, hole drilling and placement of the steel rebar, cement slurry pressure grouting, saturation with back pressure, pullout of the soil nail, and post-test examination after the test. Detailed description of the test procedures can be found in Zhou (2008).

The soil used in this study was a typical in-situ soil in Hong Kong, and classified as a Completely Decomposed Granite (CDG). The composition of the sample soil was 5.8% gravel, 44.1% sand, 36.8% silt and 13.3% clay. The cement slurry was prepared at a water-cement ratio of 0.42. The shear strength parameters of the soil are summarized in Table 1.

Table 1. Shear strength parameters of the CDG soil

Degree of saturation (S_r)	At peak		At 20% axial strain	
	c' (kPa)	φ' (deg)	c' (kPa)	φ' (deg)
98%	3.7	35.6	0	34.9

3 RESULTS AND OBSERVATIONS FROM LABORATORY TEST

A series of pullout tests have been carried out in a saturated condition. The applied vertical overburden pressure (OP) varied from 80 kPa to 350 kPa and the applied grouting pressure (GP) ranged from 0 kPa to 300 kPa.

3.1 Earth pressure variations during drilling

Drilling was conducted when the stress equilibrium had been successful established under the applied overburden stress in the box. Consequently, the initial stresses established under a given overburden stress were reduced to zero at the perimeter of the drillhole (*e.g.* stress release). As shown in Figure 2,the earth pressures near the drillhole (measured by P-Cells 1, 2, 3, and 4) reduced to small, but slightly larger than zero, values, since the four cells were placed inside the soil at a distance of about 45 mm above or below the hole perimeter. But the changes of the vertical pressures at the other two cells (P-Cells 5 and 6) were not significant, as they were about 235mm distance away from the drillhole. It should be noted that earth pressure responses were very similar to the previous test results reported by Su *et al*. (2007), Su *et al*. (2008) and Yin *et al*. (2009).

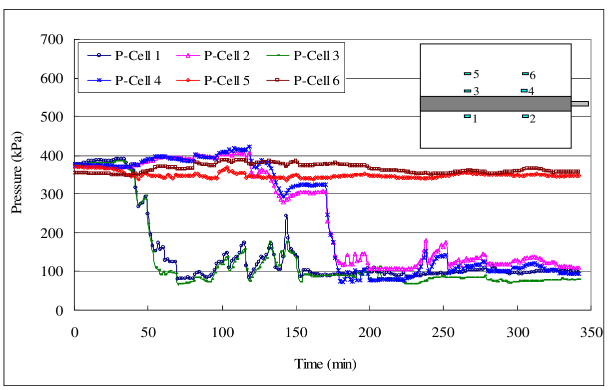


Figure 2. Relationships between earth pressures and time during drilling under overburden pressure of 350 kPa

3.2 Earth pressure variations during pressure grouting

The earth pressure responses were monitored during pressure grouting. Figure 3 shows the changes in the earth pressures at P-Cells 1 to 6 with time under GP=250 kPa and OP=350 kPa. It is seen from Figure 2 that the initial earth pressures at P-Cell 1, 2, 3, and 4 after the hole drilling and before grouting are not the same. This is because that the distances between an earth pressure cell and the soil nail surface changed with the soil settlement and soil particle re-arrangement during and after the test phases of soil compaction, overburden stress application, and hole drilling. Since the stresses, close to the perimeter of the drillhole, have dramatic variations, any small difference in the locations of the earth pressure cell above (or below) the drillhole surface will result in a big variation in the measured earth pressure. The different initial earth pressures at P-Cells 1 to 4 before grouting are also observed in other tests (Zhou 2008).

The grouting pressure was applied initially at 20 kPa for a few minutes until the hole was fully filled with cement slurry, and then gradually increased to a certain grouting pressure, *i.e.* 250 kPa in Figure 3. It is clearly observed that earth pressures at P-Cells 1 to 4 are rapidly increased to peak values; while pressures at P-Cells 5 and 6 are almost unchanged. Although the applied grouting pressure of 250 kPa in the grouting barrel was kept for 30 minutes, the increased pressures at P-Cells 1 to 4 were only maintained for about 10 minutes and then decreased gradually to stable values.

Irregular changes in earth pressures, *i.e.*, little intermittent decreases and increases, are observed in Figure 3, during the grouting. This irregular pressure change phenomenon can be explained by understanding the process of grouting under pressure in a porous soil. Immediately after the grouting pressure is applied, the pressure is first transmitted to the soil surface at the perimeter of the drillhole. The total earth (normal or vertical in the test) pressure of the soil near the drillhole perimeter is increased by the grouting pressure of the cement slurry and detected by earth pressure cells (P-Cells 1, 2, 3, and 4). If the grouting pressure is high enough, some cracks within the soil might suddenly be generated to allow the dissipation of the pore pressure in the soil, causing a sudden decrease of the grouting pressure in the drillhole. As a result, more cement slurry under the applied pressure in the grouting barrel is injected into the drillhole, and the grouting pressure in the drillhole increases again, until the cement grout in the plastic grout tube could not move at all due to the viscosity increase (or hardening) of the grout. Soil crack generation may occur more than once, resulting in several sudden decrease-increase changes as shown in Figure 3.

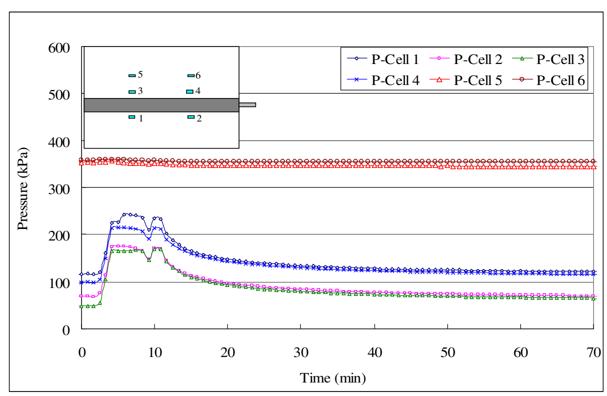


Figure 3. Relationships between earth pressures and time during pressure grouting for the tests under GP=350 kPa and OP=250 kPa.

3.3 Earth pressure variations during soil saturation

During the soil saturation, a back water pressure of 30 kPa was applied to the soil and the overburden stress was increased correspondingly, to maintain a consistent effective overburden stress. Four pore water pressure transducers (PPT) were installed to monitor the pore water pressure changes in the box during the test, as shown in Figure 4. The moisture content of the soil was measured right after the pullout test. The degree of saturation of the soil was approximately 95% around the soil nail surface after pullout. The effective vertical stresses in the box are calculated by subtracting the average pore water pressure (measured by the four PPTs) from the total stresses (measured by P-Cells 1 to 6). Since P-Cell 5 and P-Cell 6 were placed far away from the soil nail, the variations of average effective stress at P-Cell 5 and P-Cell 6 could represent the changes of the effective overburden stress. Figure 5 shows the changes in effective vertical stresses in the box with time, during saturation, for the test under OP of 350 kPa and GP of 250kPa. The soil suction, observed in the beginning of saturation in the figure, is due to the use of an air vacuum pump. It can be seen that the suction rapidly disappears as the water flows into the soil under the back pressure. It is observed that after saturation, the increase in the vertical effective stress around the soil nail (data from P-Cells 1,2,3 and 4) is larger than the increase in the effective overburden stress (data from P-Cells 5 and 6). This phenomenon reflects the collapse of the arching effect in the soil around the soil nail during saturation. When water flows into the voids in the soil, the soil particles surrounding the soil nail move and re-arrange, and the arching around the soil nail is relaxed. Thus, soils adjacent to the soil nail take a larger share of the overburden stress, so that the total earth pressures at P-Cells 1, 2, 3, and 4, to certain extent, increase.

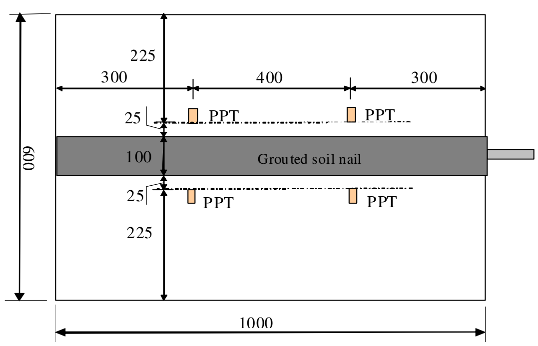


Figure 4. Locations of four pore water pressure transducers (PPT) in the soil (top view, unit: mm).

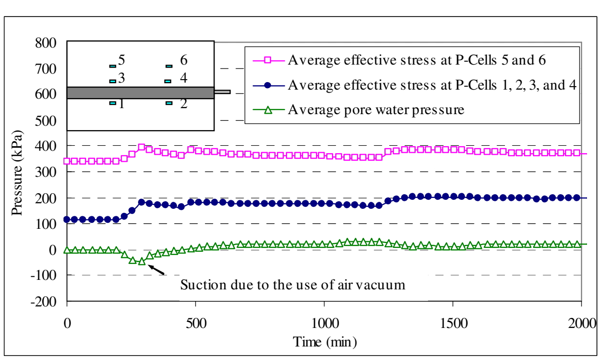


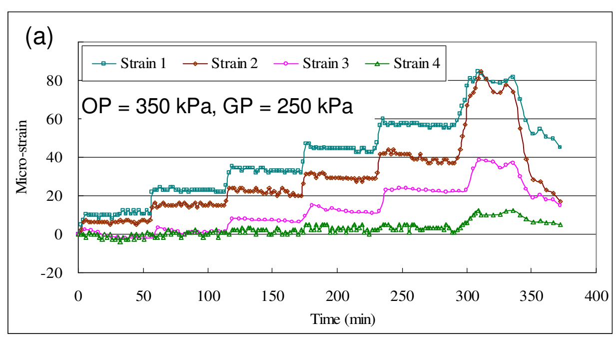
Figure 5. Variations of effective vertical stress and pore water pressure with time during the soil saturation for the test under OP = 350 kPa and GP = 250 kPa.

It should be noted that when the grouting pressure is lower, the above mentioned phenomenon is less distinct. This is because that the stress increase in the soil adjacent to the soil nail is related to the soil densification during the pressure grouting.

3.4 Results during pullout

The pullout load was applied in steps and kept unchanged for about 1 hour for each step. After reaching the peak value, since it was difficult to keep the load unchanged, the pullout load was applied at a constant displacement rate. For each pullout test, 4 electrical resistance-type strain gauges (SG) were installed along the steel rebar to measure the axial strains along the soil nail. The steel rebar was 40mm in diameter and 1.2 m in length. The strain responses were therefore relatively small, with a maximum strain of about 100 micro strains during pullout.

Figure 6 shows the monitored data during the pullout testing under OP = 350 kPa and GP = 250 kPa, (a) strains at four locations in the soil nail vs. time, and (b) pullout force *vs.* pullout displacement. It is seen from Figure 6(a) that the axial strains along the soil nail show a corresponding response at the time when the pullout force is applied step by step; the nearer to the nail head, the bigger the observed strain responses; the strains near to the end of the soil nail change little with the values below 15 micro-strains during the pullout. From Figure 6(b), it can be seen that the pullout force increases linearly with the pullout displacement in the first few millimeters, and then increases nonlinearly until the peak strain value is reached. This is followed by softening behaviour.



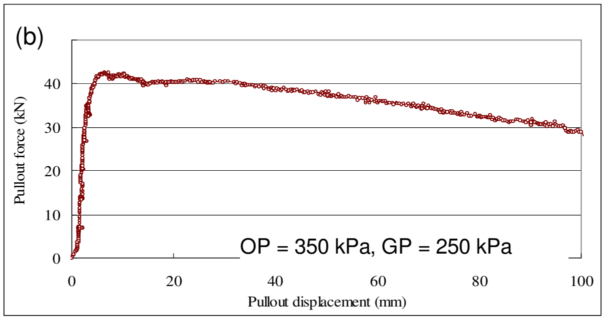


Figure 6 Monitored data during the pullout testing under OP = 350 kPa and GP = 250 kPa (a) strains at four locations in the soil nail vs. time, and (b) pullout force *vs.* pullout displacement

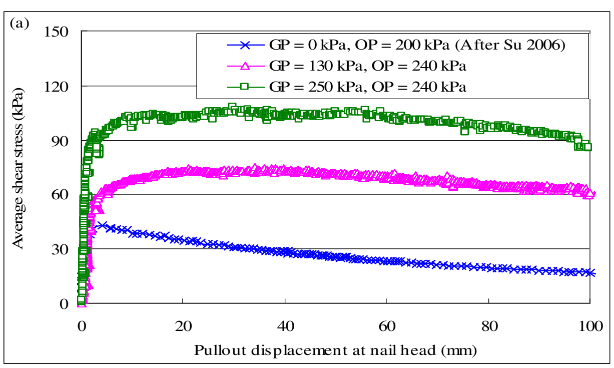
4 SUMMARY OF LABORATORY TEST RESULTS

The average shear stress at soil nail interface is more straightforward for the interpretation of soil nail pullout resistance. The average interface shear stress ($\bar{\tau}$) is calculated from the measured pullout force (*P*) at nail head divided by the active surface area of the nail,

$$\bar{\tau} = \frac{P}{\pi D L}$$

[1]

where *D* is the average diameter of the soil nail measured after pullout of the soil nail, and *L* is the length of the soil nail in contact with the soil inside the box, that is, *L*=1 m. The actual nail length was 1.2 m with 0.2 m in the additional chamber at the back of the pullout box. After grouting, the soil in the additional chamber was removed, so that the soil nail length inside the box was maintained as 1 m in full contact with soil inside the box during the pullout.



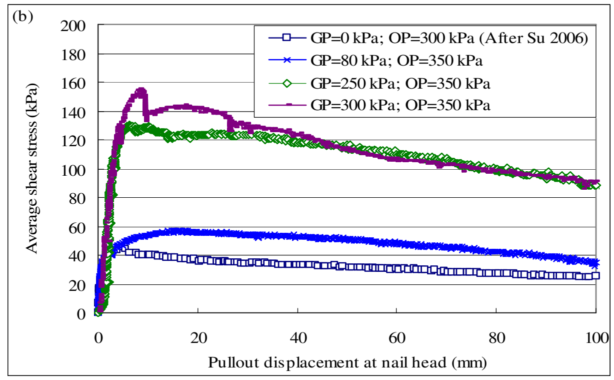


Figure 7. Variations of average interface shear stress with pullout nail head displacement under different grouting pressures (GP) and the same overburden pressure (OP): (a) GP = 130 kPa and 250 kPa, with the same OP=240 kPa (plus GP=0 kPa and OP=200 kPa from Su 2006) and (b) GP = 80 kPa, 250 kPa, and 300 kPa, with the same OP=350 kPa (plus GP=0 and OP=300 kPa from Su 2006)

Figure 7 shows the development of average interface shear stress with the pullout displacement for the tests under different grouting pressures (GP) and the same overburden stresses (OP). It is seen that under the same overburden stress, the grouting pressure clearly results in an increase in the soil nail pullout interface shear resistance compared to that for the soil nail grouted without pressure. In Figure 7(a), the test curve for GP = 0 kPa shows significant strain softening behaviour, that is, a sharp reduction in the interface shear stress with pullout displacement, while the test curves for GP of 130 kPa and 250 kPa are more ductile with minor softening behaviour. In Figure 7 (b), for the tests under condition of OP of 350 kPa without or with pressure grouting, all four curves exhibit obvious strain softening behaviour. The differences in the interface shear stress and displacement responses reflect that the grouting pressure has significant influence on soil nail pullout behaviour, especially when the grouting pressure is high.

Soil nail pullout resistance includes peak and residual pullout resistance. The peak resistance is defined as the peak average shear stress at the soil-nail interface during pullout. In the present study, the peak resistance occurs within 10 mm pullout displacement in some tests, and within 13.5 mm - 34.0 mm pullout displacement in others. The peak pullout resistance and the residual pullout resistances (defined as the interface shear stress at 50mm pullout displacement) for all tests (including the tests done by Su (2006) under grouting pressure = 0) are summarized in Table 2.

Table 2. Summary of soil nail pullout resistance under different overburden pressures (OP) and grouting pressures (GP)

GP \ OP	40 (kPa)	80 (kPa)	120 (kPa)	200 (kPa)	240 (kPa)	300 (kPa)	350 (kPa)
At peak							
0 (kPa) *	44.1	51.8	60.1	43.1	-	44.3	-
80 (kPa)	-	64.0	75.4	-	-	-	57.0
130 (kPa)	-	63.9	64.2	-	74.5	-	-
250 (kPa)	-	-	79.9	-	108.2	-	129.9
300 (kPa)	-	-	-	-	-	-	154.9
At 50 mm pullout displacement							
0 (kPa) *	36.9	33.1	26.4	25.6	-	31.7	-
80 (kPa)	-	56.4	66.2	-	-	-	51.1
130 (kPa)	-	58.3	52.8	-	71.4	-	-
250 (kPa)	-	-	54.9	-	104.7	-	116.4
300 (kPa)	-	-	-	-	-	-	112.8

* After Su (2006)

It can be seen from Table 2 that for GP = 0 kPa, and 80 kPa, the peak pullout resistance is hardly dependent on the overburden pressure; for GP=130kPa, the peak resistance increases a little when overburden pressure increases from 120 kPa to 240 kPa; but at GP=250 kPa, the peak pullout resistance dramatically increases with the overburden pressure. For the residual pullout resistances at 50mm pullout displacement, it is found they are hardly dependent on the overburden pressure for GP=0 and 80 kPa. For GP=130 kPa, the influence of overburden pressure seems emerging. The residual pullout resistance increases significantly when OP increases from 120 kPa to 240 kPa. For GP=240 kPa, the residual pullout resistance increases significantly when OP increases from 120 kPa to 240 kPa, but the increasing rate slows down when OP increases from 240 kPa to 350 kPa.

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No distinct influence of the grouting pressure is found on the peak and residual pullout resistances for OP=80 kPa and 240 kPa. However, when the overburden pressure is higher, *i.e.* OP=240 kPa and 350 kPa, a significant increase of peak resistance is observed with the increase of grouting pressure. For residual resistances, a similar trend as that of the peak resistance, except that for OP=350 kPa and GP=300 kPa, where the reduction on the residual resistance seems larger than other cases.

5 SITE CONDITIONS AND FIELD PULLOUT TEST SETUP

5.1 Site conditions and material properties

A series pullout tests were carried out in a uniform natural slope, namely Feature No.11SW-C/F220 at South of Pok Fu Lam Kennels, Pok Fu Lam in Hong Kong. This slope was under the landslide preventive measure (LPM) programme of Hong Kong Government. Site investigation works indicated that the maximum slope height was 12 m and the slope length was 26.5 m, while the slope angle varied from 15° to 48° to the horizontal. The representative soil sample obtained from the site was composed of 2% gravel, 72% sand, 17% silt and 9% clay, described as yellowish brown, clayey, very silty, slightly gravelly sand.

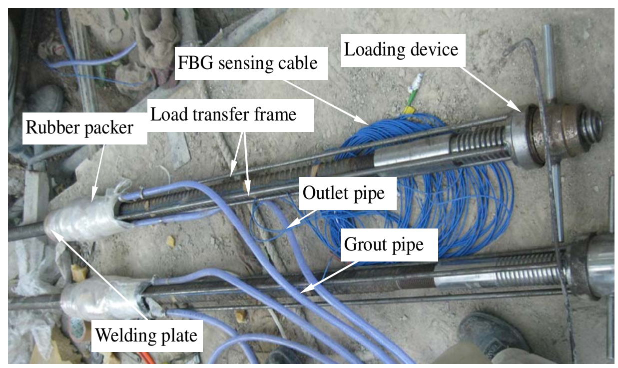

Figure 8. Full instrumentations of nail bars with fiber Bragg grating (FBG) sensors and packers before installation in drill holes.

5.2 Full instrumentation of a nail bar for pullout testing

Typical full instrumentations of nail bars with packers and fiber Bragg grating (FBG) sensors are shown in Figure 8. The installation works of the nail bar before pullout testing include: (a) the welding of a metal plate on nail bar for fixing the rubber packer; (b) the installation of a rubber packer on the nail bar for controlling the grouted length of soil nail; (c) the instrumentation of a loading frame on the nail bar for transferring external load to the rubber packer; (d) the installation of a loading device on the nail head for applying compressive load to the packer; and (e) the installation of a centralizer for fixing the nail bar at the center of the drillhole. In this study, the rubber packer was designed for controlling the grouted length of a soil nail prior to the pullout testing. With this packer, the pullout resistance of a certain grouted length can be effectively investigated. In addition, the packer allows pressure grouting on the grouted lengths, so that the effect of grouting pressure on the pullout resistance can be assessed. Working mechanism of the packer will be introduced in the next section.

5.3 Working mechanism of rubber packer

The designed rubber packer exhibits significant expansion under compressive load. This property enables the packer to seal the grouted portion of a soil nail. After a nail bar instrumented with rubber packer is placed into a drillhole but prior to cement grouting, the loading device (Figure 8) at the nail head produces compressive load to the load transfer frame, which will move along the nail bar and offers compressive deformation to the rubber packer. Afterwards, the rubber packer starts to expand in the diametrical direction of the drillhole. Due to the existence of significant expansion of the rubber packer, it can form a tight contact with the drillhole surface under the compressive load. When grouting starts, the cement grout will flow into the grouted portion through grout pipe and flow out via the outlet pipe, but will not leak through the rubber packer. According to practical field experiences, the rubber packer was available for pressure grouting on soil nails, and the maximum grouting pressure up to 160 kPa was successfully maintained in the grouted portion of a nail bar. Main features of this packer are as follows:

(a) the packer is economical and can accommodate different hole diameters, nail diameters, and grouted lengths;

(b) the packer is recyclable after the cement grout has cured. Reversible compressed and expanded deformation enable the rubber packer to be reused;

(c) the removal of packer prior to pullout testing avoids the generation of additional frictional resistance on soil nails.

5.4 Cement grouting and pullout testing of soil nails

This study attempts to investigate the effects of grouting pressure and overburden stress on the pullout resistance of soil nails. Therefore, a varied soil depth and grouting pressure are considered. Table 3 summarizes the data of grouting pressures and related soil depths of soil nails in the test. It is seen that the soil depth varied at 2 m and 6 m, whereas the grouting pressure changes at 0, 80 and 140 kPa. The diameters of drill hole and nail bars placed inside are 100 mm and 40 mm, respectively. A grouted length of 1.2 m is controlled with the designed rubber packer.

After the nail bar was placed into a drill hole and a tight contact between hole surface and rubber packer was formed, cement grouting with or without pressure can start. In this process, cement grout was pumped into the grout pipe (Figure 8) using air pressure. Once the grouted portion of the nail bar is fully filled with cement grout, the air pressure will then pump the cement grout out of the drill hole through the outlet pipe. The soil nails in the test includes two types, *i.e.* soil nails grouted without pressure or with pressure. When a soil nail is grouted without pressure, grouting is accomplished if the cement grout flows out of the outlet pipe under low air pressure. But if pressure grouting is required, a special pressure gauge must be installed on the outlet pipe to (a) seal the outlet pipe in order to maintain a high grouting pressure inside the drillhole; and (b) to measure the pressure change of cement grout. It is noted that the pressure gauge must be installed after the cement grout flow out of the drill hole through the outlet pipe. The required grouting pressure can be approached by increasing the grouting pressure in the grout pipe.

Table 3. Grouting pressures and soil depths of soil nails

Soil nail No.	Soil depth (m)	Grouting pressure (kPa)
1-0	6	0
1-1	6	40
1-2	6	80
1-3	6	140
1-4	2	0
1-5	2	40
1-6	2	80
1-7	2	140

Pullout testing was carried out 15 days after cement grouting. The pullout load was applied step by step with an increment of 5 kN. Each loading increment was maintained for 5 minutes. After approach the peak pullout force, the soil nail was pulled out continuously at a speed of 1 mm per minute to achieve a maximum pullout displacement of 50 mm. During the pullout process, strain results of FBG sensors on the nail bar were collected using interrogator.

6 EFFECTS OF GROUTING PRESSURE AND OVERBURDEN STRESS ON THE PULLOUT RESISTANCE

The average pullout shear stress was calculated using Eq.(1). Figure 9 (a) and (b) show the development of average shear stress of field soil nails with pullout displacement at the soil depths of 2 m and 6 m, respectively. It is seen in Figure 9 (a) that the average shear stress of soil nail is generally larger when the grouting pressure is higher. The average pullout shear stress at higher grouting pressure show slight strength softening behaviour. But for the soil nails grouted at a depth of 6 m as shown in Figure 9 (b), the average shear stress displays a significant strength softening behaviour when the grouting pressure is high, but this observation is not clear when the grouting pressure is low. In addition, the average shear stress is obviously much larger at higher grouting pressures. Therefore, it is drawn that the pullout shear strength of soil nail interface can be enhanced by pressure grouting on soil nails.

Figure 10 shows the peak pullout resistance of soil nails at different grouting pressures and soil depths. It is seen that, with the increase of grouting pressure from 0 kPa to 80 kPa, a slight growth in the peak shear stress of soil nails is observed. But as the grouting pressure approaches 140 kPa, the related pullout shear stress exhibits a significant increase. In addition, the fitted straight line (full line in Figure 10) of the peak shear stress at the depth of 6 m presents above that (dashed line in Figure 10) at the soil depth of 2 m. This can be interpreted as that, when soil nails were grouted with pressure, the overburden stress (soil depth) can also enhance the shear strength of the soil nail interface.

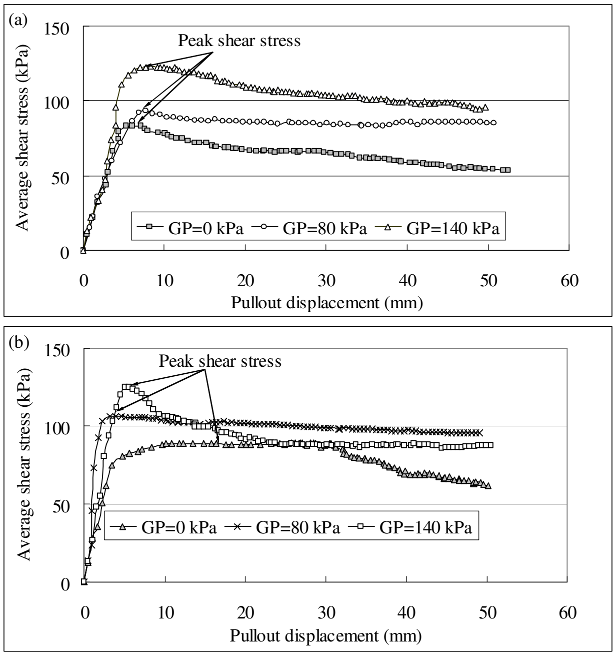

Figure 9. Development of field average shear stress of soil nails with pullout displacement when soil depth is (a) 2 m and (b) 6 m.

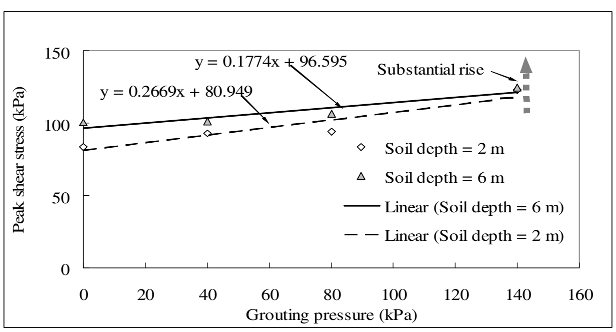

Figure 10. Peak shear stress of soil nails at different soil depths

As reported by Yin and Zhou (2009) and Yin *et al.* (2009), there exists an interaction effect between overburden stress and grouting pressure, *i.e.*, for pressure-grouted soil nails, the overburden stress and grouting pressure will interact with each other, leading to a further increase in pullout resistance of soil nail. The observations of the field pullout test results are fully consistent with the above observations. Therefore, it can be drawn that, for field soil nails grouted with pressure, soil nail interface can build up higher pullout shear strength when either grouting pressure or overburden stress is greater.

7 SUMMARY AND FINDINGS

The authors have conducted a series of laboratory soil nail pullout tests on a nearly saturated Completely Decomposed Granite (CDG) soil and a total of 8 field pullout tests under a combination of different overburden stresses and grouting pressures. Typical results from all these pullout tests are presented and discussed. Data from all tests have been analyzed and interpreted together to examine the effects of both grouting pressure and overburden stress on the soil nail interface shear strength. Based on the above presentation and discussion, the following observations and findings are obtained:

(a) During the pressure grouting, the stresses around the drillhole are rapidly increased by the applied grouting pressure inside the hole, but then drop quickly due to hardening of the cement grout in the grouting pipe and in the drillhole.
(b) During the saturation, the vertical stresses around the soil nail increase to a certain extent. This phenomenon reflects the collapse of the arching effect and the soil particle re-arrangement in the soil around the nail.
(c) Both overburden stress and grouting pressure have influences on soil nail pullout resistance, and their influences are interactional. The soil nail pullout resistance is hardly or slightly dependent on the overburden stress when the grouting pressure is low, but increases with the overburden stress when the grouting pressure is higher.
(d) For field pullout tests of pressure grouted soil nails, the pullout shear stress of soil nails appears to increase with both the grouting pressure and overburden stress.

It should be noted that the interpretation of test data in this paper is based on data from a limit number of laboratory soil nail pullout tests and field pullout tests on a local soil in Hong Kong. The results and findings are valuable for soil nailing design in Hong Kong. However, caution should be taken for any extension of the findings for other soils and under other test conditions.

ACKNOWLEDGEMENTS

Financial supports from a grant from Research Grants Council (RGC) General Research Fund (GRF) (grant number: PolyU 5320/07E) of the Hong Kong Special Administrative Region Government of China and from The Hong Kong Polytechnic University are gratefully acknowledged. Authors acknowledge the support-in-kind from Ove Arup & Partners Hong Kong Limited, Mr Raymond W. T. Cheung and Mr C. K. Tse for the field pullout tests. The authors wish to thank Ir Albert Ho for his advice and help on the field pullout tests. The authors appreciate the assistance from Mr YP Leung on laboratory tests.

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