Distributed optical fibre strain sensing for instrumentation of soil nail pull out test

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ABSTRACT

For the past few years, there has been rapid development in the area of smart sensor technologies, in particular by using structurally integrated optical fibre sensor to form the basis of smart structure technology. Recently, Brillouin Optical Time-Domain Analysis (BOTDA) has been implemented successfully in pile load tests. BOTDA is a distributed optical fibre sensor that allows measurement of strain along the full length (up to 100km) of a suitably installed optical fibre. In this paper, utilisation of BOTDA to replace vibrating wire strain gauges in soil nail pull out test in granite formation will be discussed. The load distribution along the soil nail length during the pull out test is presented in this paper as well. In addition, the empirical correlation between the mobilised soil shaft friction and Standard Penetration Test value, SPT'N along the soil nail length will also be discussed.

Keywords: distributed optical fibre strain sensing, soil nail, pull out test, granite formation

1 INTRODUCTION

For the past few years, there has been rapid development in the area of smart sensor technologies, in particular by using structurally integrated optical fibre sensor to form the basis of smart structure technology and this have been reported by C.Y.Hong et al. (2016). Recently, Brillouin Optical Time-Domain Analysis (BOTDA) has been implemented successfully in pile load tests (Hisham Mohamad et al. (2017))p. However, there is limited case study on usage of BOTDA as instrumentation device for soil nail pull out test in Malaysia.

Basically, soil nails are reinforcing, passive elements that are drilled and grouted sub horizontally in the ground to enhance stability of cut slopes in soil, or in soft and weathered rock. In Malaysia, reinforcement bars such as T25 and T32 are generally adopted as the reinforcing element.

In this paper, utilisation of BOTDA to replace vibrating wire strain gauges in soil nail pull out test in granite formation will be discussed. The load distribution along the soil nail length during the pull out test will be presented. In addition, the empirical correlation between the mobilised soil shaft friction and Standard Penetration Test value, SPT'N along the soil nail length will also be discussed.

2 SOIL NAIL PULL OUT RESISTANCE

The soil nailing technique improves the stability of slopes principally through the mobilisation of tension in the soil nails. The resistance against pullout failure of the soil nails is provided by the part of soil nails that is embedded into the ground behind the potential failure surface. Therefore, pullout resistance is one of the key parameters for the design of soil nails

Basically, there are several approaches, namely empirical correlation, undrained shear strength method and effective stress method etc to estimate the pull out resistance of soil. Each method has its own merits and limitations in accounting for the factors such as soil type, soil shear strength, surface roughness, grouting pressure and groundwater conditions.

Generally, empirical correlation with SPT'N (Standard Penetration Test) value is adopted in Malaysia to estimate the pull out resistance (i.e bond stress between ground and grout) of soil nail. The empirical correlation factors are in the range of 3 to 5. Hence, it is vital to verify the adopted empirical correlation factor to ensure the safe and cost-effective design.

3 PULL OUT TEST

3.1 Current Common Practice

Instrumented pull out test is generally carried out prior to the installation of working soil nails to verify the designed pull out resistance (i.e bond stress between ground and grout) of soil nail. Vibrating wire strain gauges (VWSG) are normally deployed to measure the strain of the soil nail and thus to determine the pull out resistance. However, this approach is unable to provide continuous strain profile along the soil nail.

As such, Brillouin Optical Time-Domain Analysis (BOTDA) is utilised to replace VWSG in 2 sites (Site A and Site B) in instrumented pull out test in order to acquire continuous strain profile along the soil nail.

Both Site A and Site B are located in Granite formation. The load distribution along the soil nail, empirical correlation with SPT'N to estimate pull out resistance, will be discussed in the following sections.

3.2 General Geological Formation

Based on the Geological Map of Pulau Pinang and Butterworth Area, New Series L7010, Sheet 28, published in 2014 by the Director-General of Minerals and Geoscience Department Malaysia, the proposed sites are underlain by Tanjung Bunga Granite with Early Jurassic age. Tanjung Bunga Granite generally consists of fine-grained megacrystic biotite granite. The overburden material generally consists of silty SAND or sandy SILT, which is derived from granite. The geological map of these sites is shown in Figure 1.

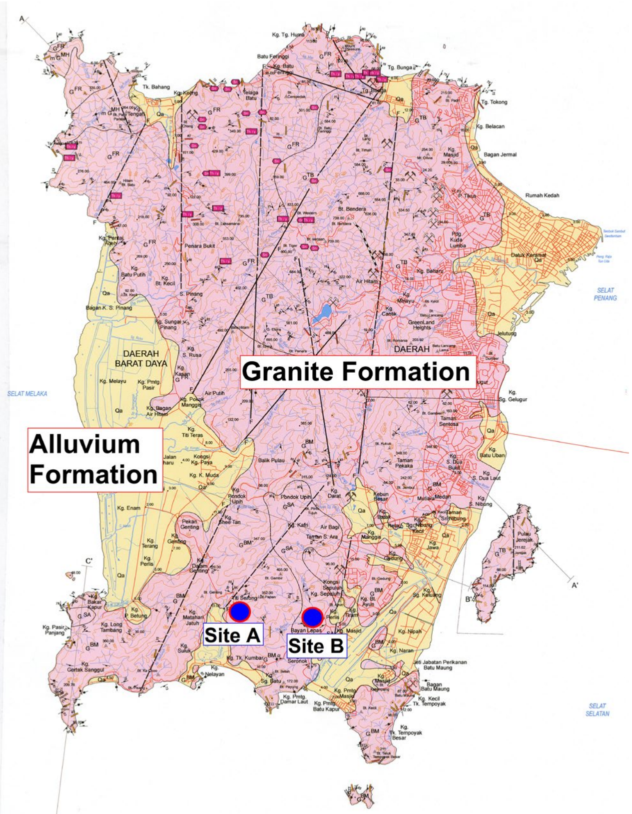

Figure 1. General Geological Map

3.3 BOTDA Instrumented Pull Out Test

BOTDA instrumented pull out tests were carried out for preliminary soil nail (non-working soil nail) for both Site A and Site B. The details of the preliminary pull out tests are summarised in Table 1. Whilst, Figure 2 shows the simplified borehole profile indicating the SPT-N values, major/minor components of soil and Rock Quality Designation (RQD) for rock. Both soil nails are 6m length with reinforcement bar of T32 slotted inside a 125mm diameter drilled hole. The distributed fibre optic strain sensing cable is attached along the full length of soil nail steel reinforcement with cable ties. Typical set-up for the pull out test is shown in Figure 3 with the details of the BOTDA instrumented preliminary soil nail is shown in Figure 4.

Table 1. Details of Instrumented Pull Out Test on Preliminary Soil Nail (Non-working Soil Nail)

Site	Bar Diameter (mm)	Maximum Test Load Achieved (kN)	Nearest Borehole
A	32	200	BH7
B	32	175	BH-FV11

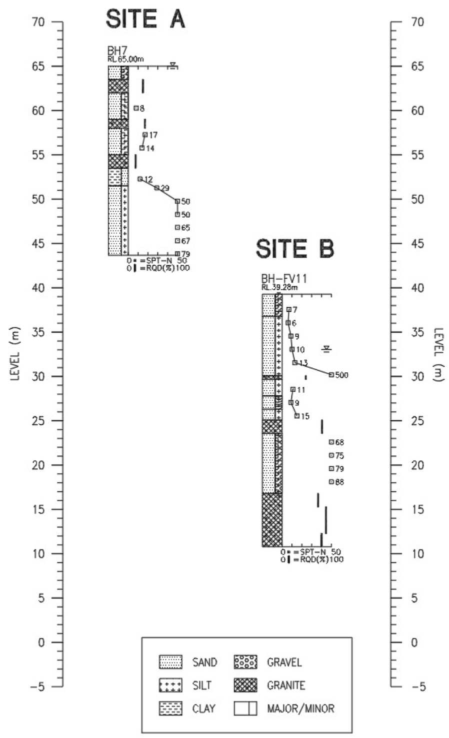

Figure 2. Nearest Borehole Profiles for Both Preliminary Soil Nails

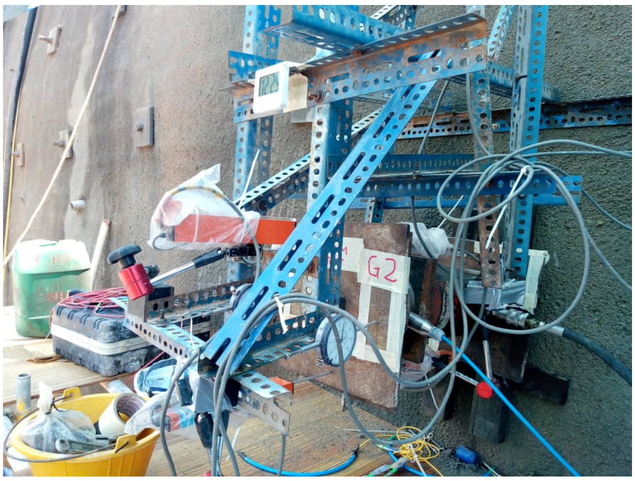

Figure 3. Typical Setting Up for Pull Out Test

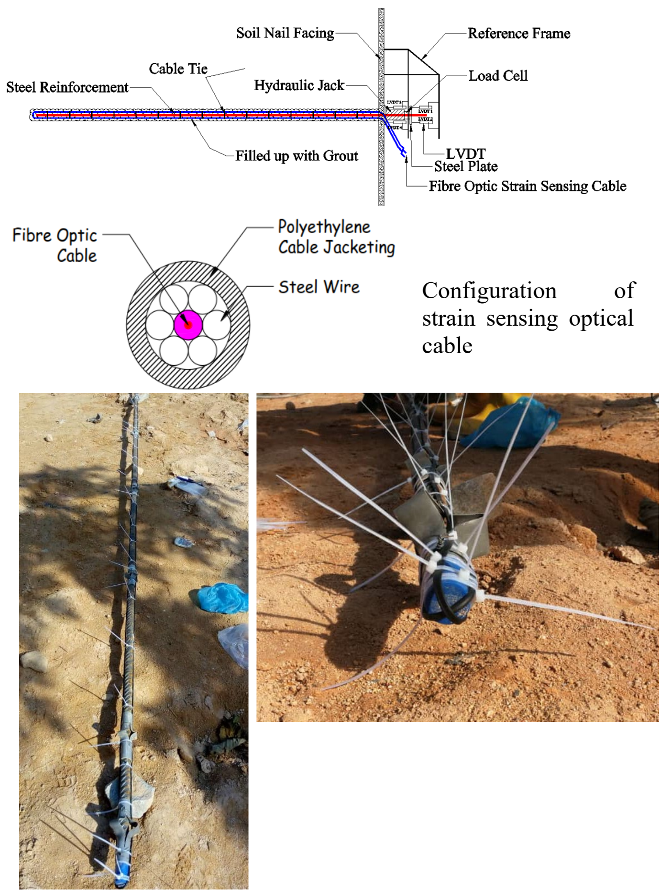

Figure 4. Details of BOTDA Instrumented Preliminary Soil Nail

3.4 Calculation on Shaft Friction

The unit shaft resistance from one level to another level of soil nail is calculated from the Eq. (1).

$$Fs = \frac{P}{\pi D \times L} \tag{1}$$

where
Fs = Shaft friction, P = Load at the particular level
D = Diameter of soil nail, L = Distance between sensor levels

Whilst, strain along the soil nail is measured by using BOTDA and load at the particular level is calculated from the Eq. (2).

$$P = \mathcal{E}EA \tag{2}$$

where
P = Load at the particular level, $\mathcal{E}$= Average change in strain
EA = soil nail's stiffness

3.5 Results of Instrumented Pull Out Test

The test procedures and testing sequence of the preliminary pull out test are carried out in accordance with FHWA 1998 and the loading schedule is shown in Table 2. The loading distribution graphs along soil nail length are shown in Figures 5 and 6 for Site A and Site B respectively. Whilst, the pull out test results showing the mobilised shaft friction versus average strain of soil nail for Site A and Site B are shown in Figures 7 and 8 respectively.

Table 2. Loading Schedule for Preliminary Pull Out Test (FHWA, 1998)

Load Increment	Holding Time (minutes)
0.25 DTL	10
0.50 DTL	10
0.75 DTL	10
1.00 DTL	10
1.25 DTL	10
1.50 DTL (creep test)	60
1.75 DTL	10
2.00 DTL	60
Repeat cycle if soil nail could be tested up to 3.00 DTL	

Notes:
1. DTL = Design Test Load.
2. Test load limited to maximum 80% yield strength of nail reinforcement.
3. Creep test to be performed at 1.50 DTL. Holding duration (either 10 minutes or 60 minutes) is depending on nail performance. Where the nail movement between 1 minute and 10 minutes exceed 1mm, the holding duration will be extended to 60 minutes.

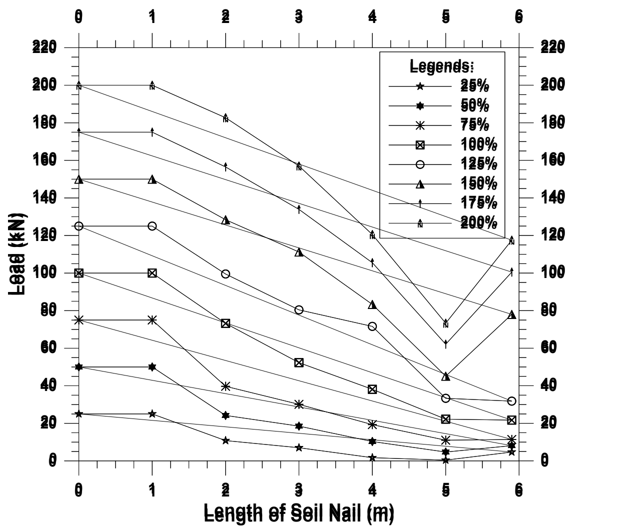

Figure 5. Load Distribution along Soil Nail Length for Site A

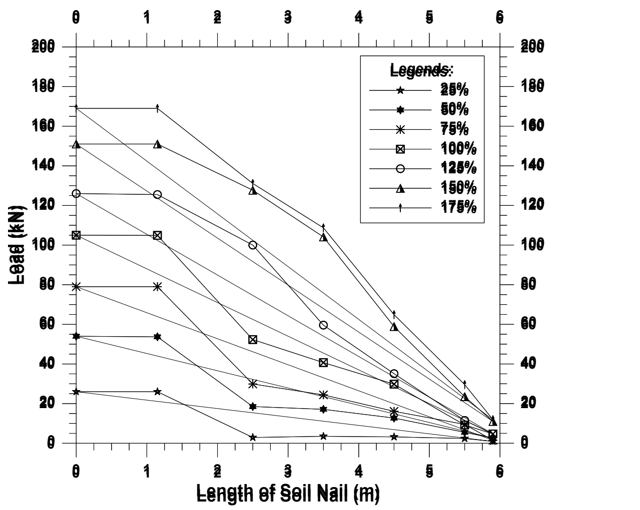

Figure 6. Load Distribution along Soil Nail Length for Site B

Based on Figures 5 and 6, it can be seen that the load decrease gradually along the soil nail length due to contribution of pull out resistance of soil nail from the shaft resistance. However, significant strain increased at end of soil nail (indicated load increased) were recorded during the pull out test for Site A. Generally, a constant soil nail stiffness (in the function on change of strain) is adopted to estimate the load distribution along the soil nail based on the measured strain. However, if there is mixture of soil with grout at the end of the drilled hole (where the soil is unable to be displaced fully by the grout during grout injection), the stiffness of soil nail will be overestimated and thus lead to higher estimation on load at the end of the soil nail. Therefore, the load increased at end of soil nail for Site A are likely due to mixture of soil and grout, which affected the instrumented test results.

Whilst, based on Figures 8 and 9, the following observations could be made:

a) The SPT'N values at the level of the tested soil nails typically range from 8 to 17 for Site A and from 6 to 15 for Site B respectively.
b) The mobilised shaft frictions recorded range from 60 to 120kPa for Site A. Whilst, the recorded shaft frictions for Site B are ranging from 90kPa to 120kPa for Site B.
c) This indicate a conservative empirical correlation of 5 x SPT'N can be adopted to estimate the pull out resistance of soil for soil nail design in granite formation. This is in lined with observation by Chow & Tan (2013).

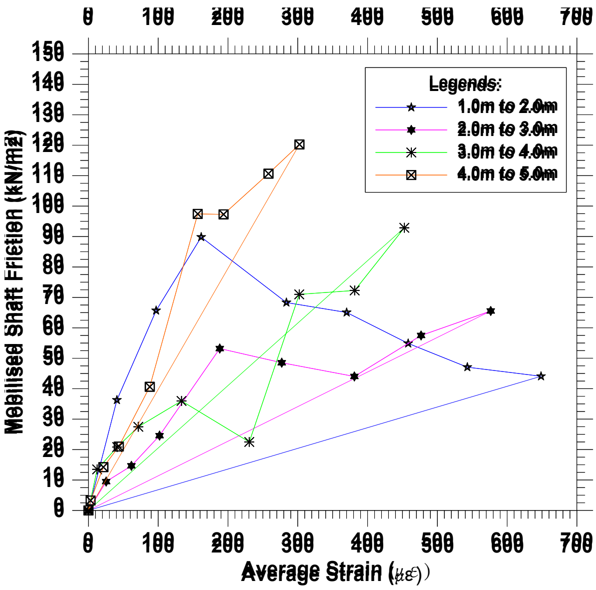

Figure 7. Mobilised Shaft Friction vs. Average Strain for Site A

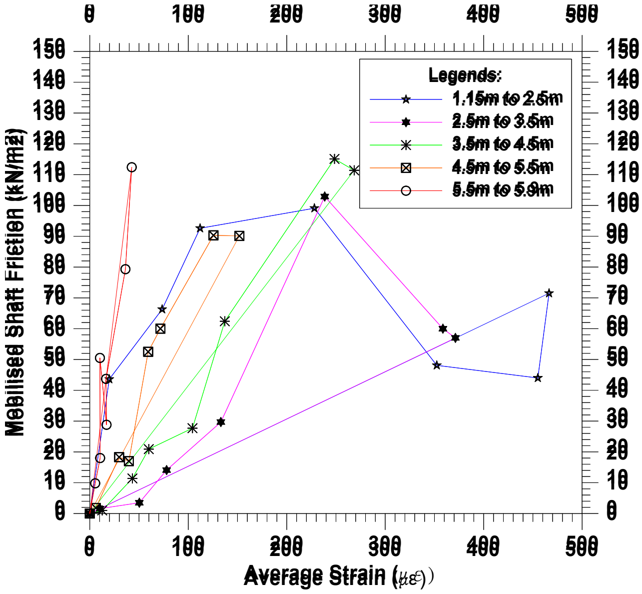

Figure 8. Mobilised Shaft Friction vs. Average Strain for Site B

4 CONCLUSIONS

Brillouin Optical Time-Domain Analysis (BOTDA) is utilised to replace VWSG in 2 sites (Site A and Site B) in instrumented pull out test in order to acquire continuous strain profile along the soil nail. The two instrumented pull out test results by adopting BOTDA which have been presented above indicated that a conservative empirical correlation of 5 x SPT'N can be adopted to determine the pull out resistance of soil for soil nail design in granite formation.

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