High resolution time domain reflectometry and coaxial cable for soil nail monitoring

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Abstract. Soil nailing is a popular application in soil slope stabilization. Failure of soil nailing could be mainly due to the issue of installation such as inaccuracy of actual length of the soil nail and integrity of cement grout annulus during grouting. This study focuses on using non-destructive technique of time domain reflectometry (TDR) to monitor the quality of soil nail. TDR is originally used to detect changes in geometry and electromagnetic properties (dielectric or magnetic) happening along its transmission cable and detect the damage or leakage from the cable. The objective of this study is to use high resolution TDR and coaxial cable to detect changes of grout condition in soil nail. Results confirm the suitability of high resolution TDR and coaxial cable to detect void length which relates to grout condition in soil nail. The findings conclude that high resolution TDR model T631 and coaxial cable type RG-6 are capable to detect even small size void and is suitable to be applied for soil nail monitoring.

1. Introduction
Slope stabilization methods such as ground anchor, soil nailing, geo grid, etc. are commonly applied in Malaysia. The quality of slope stabilization depends on site supervision and controls during the construction works. Non-destructive test (NDT) such as time domain reflectometry is found suitable to monitor the quality of soil nail. [1] had conducted a study in Hong Kong to examine the suitability of several NDT in soil-nailing monitoring where TDR is proposed as one of the most effective methods to inspect soil nail quality.

Using TDR in soil nail inspection requires a transmission cable to be pre-installed alongside the rebar. After the grouting work, pulse will be transmitted by TDR and travels in the transmission cable. The polarity of the waveforms is then interpreted to determine the cement grout quality and the length of rebar [2]. Monitoring soil nail quality using TDR is still new to Malaysia and has good potential development. Oversea, soil nail monitoring by TDR has been widely adopted in many slope projects especially in Hong Kong. It is used to monitor the soil nails condition in high risk slopes. This study focuses on using high resolution TDR and coaxial cable to monitor grout condition in soil nail. Coaxial cable serves as the transmission cable to detect void length that encountered in soil nail as well cement grout length. The study was conducted in laboratory and soil nails were constructed with different discontinuity lengths of grout in the middle.

2. TDR Specification and Testing Program
2.1. Samples of Soil Nail
Five soil nails namely N1 – N5 were prepared by using PVC pipes (Figure 1). The soil nails had fix diameter of 10cm, length of 200cm and rebar 6mm in diameter. Sample N1 had full length of cement...
grout without void and was used as the control sample to detect the grout length as shown in Figure 2(a). Samples N2 – N5 had different void lengths in the middle, i.e., 30cm, 70cm, 90cm and 120cm to simulate different possible void condition at site. The mix design of cement grout was: sand to cement ratio is 1: 3; water to cement ratio is 1: 2. Cement grout was filled in the pre-determined area in the soil nail as shown in Figure 2(b).

Coaxial cable type RG-6 was placed alongside the rebar before grouting. Before the test started, the length of the cable was calibrated by TDR model T631. The purpose of the calibration was to ensure the length estimated by TDR was same as the soil nail sample. The estimated length is formulated through a factor called pulse propagation velocity, $v_p$. The relationship of the estimated length and pulse propagation velocity is expressed in Equation (1).

$$L = v_p t$$  \hspace{1cm} (1)

where $L$ is the length of coaxial wire between the point of pulse generator and the point of pulse discontinuity, and $t$ is the respective pulse travel time.

The pulse propagation velocity, $v_p$, is related to the electrical properties of the cable RG-6 and can be expressed by Equation (2) [3]:

Figure 1. PVC pipe used for soil nail Preparation

Figure 2. Schematic diagram of soil nail samples
\[ v_p = \frac{v_c}{\sqrt{\varepsilon}} \]  

(2)

where \( v_c \) is the speed of light in vacuum \((3 \times 10^8 \text{ m/s})\) and \( \varepsilon \) is the dielectric constant, which measures how a material reacts under a steady-state electric field (for air \( \varepsilon \approx 1 \), and for cement grout \( \varepsilon \approx 10 \)).

2.2. TDR Model T631

TDR Model T631 is a pulse reflection cable test set, which is originally applied to locate cable faults and evaluate changes in impedance caused by connectors, taps, terminations etc. In this study, the TDR transmits pulse into a cable to generate waveforms based on the grout condition in soil nail. T631 has a range of pulse width, 2, 10, 30, 100, 300 or 1200 ns for selection. The smallest pulse width of 2ns was selected in this study to detect the existence of void in soil nail. Photo of TDR model T631 is shown in Figure 3 and the specifications of TDR T631 is summarised in Table 1.

![TDR model T631](Figure 3. TDR model T631)

| Specifications of TDR T631 [4] |
|--------------------------------|
| **RANGES:** 0-3 m to 0-12 kms full screen, in 13 ranges (zoom of x2, x4, or x8 around cursor, depending on range) |
| **ACCURACY:** Typically < 0.5% |
| **RESOLUTION:** ± 0.05% of range at 12 kms |
| **PROPAGATING VELOCITY:** |
| PVF: Variable 0.300 to 0.999 |
| V: 90 to 300 m/μs |
| V/2: 45 to 150 m/μs |
| **PULSE CHARACTERISTICS:** |
| Width: 2, 10, 30, 100, 300 or 1200 ns, user selectable |
| Output Impedance: 50, 75 or 93 Ohms, user selectable |
| Noise Reduction Filter: 16 MHz Low pass |
| **OUTPUT:** |
| Socket |
| Protection: 250 V rms, 0-60 Hz |
| **DISPLAY:** |
| Type: High resolution LCD with backlighting (switchable) |
| Cursor: Two active cursors with individual control |
2.3. Coaxial Cable RG-6
Coaxial cable RG-6 is chosen because the cable is stiff and can be easily installed alongside the rebar (Figure 4). The diameter of the cable is 8.4mm in diameter and length is same as the rebar. As the properties of insulating material inside the cable is fix and independent of grout condition, the pulse propagation velocity of the coaxial cable can be obtained reliably from the respective pulse travel time between the point of pulse generator and the point of discontinuity. Small holes with interval distance of 20cm is pre-drilled on the wire to expose the wire conductor to the grout condition [5]. As the pulse travels in wire, it can detect the grout condition or existence of void in soil nail grout.

![Figure 4. Coaxial cable RG-6](image)

3. TDR Testing and Result Interpretation
Each sample of soil nail will be repeatedly tested using TDR model T631 after grouting. The lengths of cement grout and void are determined based on the polarity of the reflection of the waveform generated by TDR [6]. In cement grout area, the waveform is expected in negative reflection, it is mainly because of the amount of changes in electrical impedance at the location with cement grout. Similarly, a positive reflection will be seen when a pulse travel from cement grout to void because of an increase in electrical impedance.

The polarity of reflection can be expressed in terms of the reflection coefficient, $\Gamma$ [7]:

$$\Gamma = \frac{Z - Z_o}{Z + Z_o}$$  \hspace{1cm} (3)

where Z is the electrical impedance at the point of reflection and $Z_o$ is the characteristic electrical impedance of the transmission cable.

During the test, the waveforms of sample N1 – N5 were recorded and transferred to a software called X600 TRACEability for further analysis. The analysis procedures of X600 TRACEability can be found in the online manual [8]. The waveforms after grouting were observed and compared to the waveforms before grouting. From the comparison, the length of the cement grout and the length of void were able to be differentiated. The waveform of cement grout is in negative reflection while the waveform of void is positive. Figure 5 shows the types of waveform before and after the grouting of soil nails.
4. Result and Discussion

4.1 Performance of TDR Estimation

Performance of TDR in void length estimation is expressed as void length error. The void length error is calculated based on the deviation between estimated void length and actual void length as shown in Equation (4). When higher percentage of void length error is encountered, the accuracy of TDR in void length estimation is lower.

\[
TDR \text{ void length error (\%) } = \frac{abs(estimated \text{ void length} - actual \text{ void length})}{actual \text{ void length}} \times 100
\] (4)

Figure 6 summarises the results of void length error. In overall, the void length error varies from 0.5% to 23.3%. Results of sample N1 with full grout is the estimated grout length comparing to the actual grout length. Sample N1 has gained high accuracy with corresponded errors less than 10% and this further confirms that the coaxial wire is suitable to estimate the grout length of soil nail. Results also shows that sample N5 with void length 1.2m generating consistent and high accuracy data with errors less than 10% except one reading on 20.5%. As for sample N2 – N4, the data encountered wider distribution, varies from 2.9% to 23.3%. The average of void length error of sample N2 – N4 is 12.1%. Data with wider range of error distribution was due to the consistency issue which is explained later.
Figure 6. Distribution of TDR void length error of sample N1 – N5

4.2 Detection of Void in Soil Nail

Efficiency of void length detection in soil nail depends on the void length and the spatial resolution of TDR. Previous study shows that certain TDR model was unable to detect void lower than 55cm length from the waveform [9]. However, sample N2 in this testing has shown that the smallest void length of 30cm detected among all samples. In Figure 7, clear positive reflection of waveform in void area is detected using TDR T631. These results further confirm that the high resolution TDR T631 is suitable to monitor void length as small as 30cm in soil nail.
4.3 Consistency of TDR Estimation

The TDR data corresponded to the range of void length error are tabulated in Table 2. It shows that 58.3% of TDR data are having error less than 10%. The data in the ranges of 10% to 20% and greater than 20% are 29.2% and 12.5% respectively.

| TDR void length error (%) | Frequency of TDR readings |
|---------------------------|---------------------------|
| ≤ 10%                     | 14 (58.3%)                |
| 10 – 20%                  | 7 (29.2%)                 |
| > 20%                     | 3 (12.5%)                 |
| Total TDR readings        | 24 (100%)                 |

Table 2. Frequency of TDR void length error

However, analysis of TDR median accuracy have been carried out to further understand the consistency of the data. Median accuracy is calculated based on the TDR estimated lengths obtained from the samples. Accuracy is determined based on Equation (5). The summary of median accuracy is tabulated in Table 3.

\[
TDR \text{ median accuracy} = 1 - \frac{\text{abs}(\text{Median estimated void length} - \text{actual void length})}{\text{actual void length}} \tag{5}
\]
Table 3. TDR median accuracy of estimated void length

| Sample type | Actual void (grout) length | Median of estimated void (grout) length | Accuracy of Median values |
|-------------|----------------------------|----------------------------------------|--------------------------|
| N1          | (2.0 m)                    | (2.05 m)                               | 0.98                     |
| N2          | 30 cm                      | 27 cm                                  | 0.88                     |
| N3          | 70 cm                      | 72 cm                                  | 0.97                     |
| N4          | 90 cm                      | 101 cm                                 | 0.88                     |
| N5          | 120 cm                     | 116 cm                                 | 0.97                     |

The results show the median of estimated void length having high accuracy and ranging from 0.88 to 0.98. However, this median accuracy is deviated from the results of the estimated void lengths, which has wider error distribution. The deviation between these two data presentations; TDR estimated void lengths and median accuracy, is mainly due to the distance between the pre-drilled small holes on the coaxial cable. Closer distance of small holes on cable will give better exposure of conductor in wire to detect the grout condition when the pulse travels along the wire. This study has adopted a control of hole distance of 20cm apart.

5. Conclusion and Recommendation

Soil nail monitoring by TDR has potential development and application for slope projects in Malaysia. TDR model T631 with high resolution is suitable to detect void length 30cm in soil nail. Coaxial wire type RG-6 can detect nail length and void length with high accuracy. However, void length detection is inconsistent as compared to the grout length detection. It may be due to the existence of small holes on wire. The function of small holes is to expose wire conductor to the discontinuity of grout condition. Further study on the spacings of the small holes on the coaxial wire of void detection is suggested.

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