Journal of GeoEngineering, Vol. 11, No. 3, pp. 143-149, December 2016
http://dx.doi.org/10.6310/jog.2016.11(3).4

LABORATORY EVALUATION OF SOIL-NAILING QUALITY INSPECTION BY AN IMPROVED TDR METHOD

Chih-Chung Chung [1], Chih-Ping Lin [2*], Yin-Jeh Ngui [3],
Kai Wang [3], and Chun-Hung Lin [4]

ABSTRACT

Time Domain Reflectometry (TDR) was recently introduced as the most effective non-destructive testing method for soil-nailing inspection. Current practice of TDR inspection was conducted through a pre-installed single-core electric wire alongside the rebar within the soil nails. However, the aforementioned practice is shown to be hindered by its inability to decouple the effect of rebar length from possible grout defects, and by excessive overestimation of rebar length if the wire is coiled around the rebar. A new TDR waveguide construction and a corresponding decoupled data reduction method (for both soil-nail length and grout condition inspection) were proposed in this study. Feasibility and advantages of the new approach were experimentally verified with two types of TDR device. Based on the proposed methodology, a portable, low-cost, and low-speed TDR device was shown to suffice as a quick and economical tool for quality inspection of soil-nailing works.

Key words: Soil nail, quality inspection, non-destructive testing (NDT), time domain reflectometry (TDR).

1. INTRODUCTION

Soil-nailing is an effective, cost-effective, and widely-used technique for enhancing the stability of slopes and retaining walls (Chan 2008). Quality assurance of the as-built length and integrity of cement grout annulus is critical to the success of a soil-nail system. However, complete supervision at all times during construction stage is inefficient and not cost-effective in practice. Non-destructive testing (NDT) methods are desirable to provide quick inspections of installed soil nails and allow independent site audits after construction. A number of NDT methods, including the sonic echo, mise-a-la-masse, electromagnetic induction, and electrical resistance methods, magnetometry, time-domain reflectometry (TDR), and surface wave time domain reflectometry (SWTDR) were examined in Hong Kong (Cheung 2003; Cheung and Lo 2005; Lee and Ove Arup & Partners Hong Kong Limited (OAP) 2007).

Among these potential NDT methods, TDR was found to be the most effective after being supported by a large number of field measurements and a pilot quality assurance program (Lee and Ove Arup & Partners Hong Kong Limited (OAP) 2007). Guidelines on TDR testing procedure and interpretation of test results can be found in Cheung (2006). Cheung and Lo (2011) further examined various sources of uncertainties in soil-nail length estimation using TDR. Two categories of uncertainties are revealed. One is nail-independent uncertainty, including built-in error of testing instrument and human judgment (single and multi-operator). The other is nail-dependent uncertainty, including wire type, grout annulus (age, integrity, and characteristics), and reinforcement (diameter, length, and connectors). In order to deal with pertinent uncertainties as much as possible, they introduced guidelines on testing procedures and the interpretation of test results.

Current practice of the Hong Kong TDR method for quality inspection of soil nails involves pre-installing an electrical wire alongside the steel reinforcing bar to form a twin-conductor transmission line. A TDR device sends an electromagnetic (EM) pulse travelling along the transmission line and receives reflections induced by any impedance discontinuity (*i.e.,* change in conductor geometry or grout condition) within the line. Once the pulse-propagation velocity along the soil-nail transmission line is pre-determined and calibrated, the soil-nail length can be estimated from the pulse travel time between the reflections from the head and the end of the soil nail.

Two drawbacks of TDR method were identified: (1) Single-core electrical wire can be easily coiled around the rebar, leading to excessive overestimation of TDR-deduced soil-nail length; (2) Determination of soil-nail length becomes unreliable if the grout annulus is irregular or defective. Zostrich Geotechnical (2016) showed a similar configuration to determine the length of the rock bolt and soil nail using TDR. A coaxial (or twisted pair or fiber optic) cable is attached to the rock bolt and soil nail, and attached to a connector with a serialized endcap, which provides a unique electronic serial number for practice of quality inspection of soil nails. However, the aforementioned drawbacks were still not addressed. To overcome these problems, this study further introduced a modified and improved TDR method for enhancing the reliability of soil-nail length determination while at the same time providing independent quality assessment of the cement grout. The performance of the new approach was evaluated and validated by laboratory physical models.

Manuscript received March 10, 2016; revised May 19, 2016; accepted July 5, 2016.
[1] Assistant Professor, Department of Civil Engineering, National Central University, 300 Zhongda Rd., Zhongli District, Taoyuan City, Taiwan.
[2] Professor (corresponding author), Department of Civil Engineering, National Chiao Tung University, 1001 Ta-Hsueh Rd., Hsinchu, Taiwan (e-mail: cplin@mail.nctu.edu.tw).
[3] Ph.D. Student, Department of Civil Engineering, National Chiao Tung University, 1001 Ta-Hsueh Rd., Hsinchu, Taiwan.
[4] Assistant Research Fellow, Disaster Prevention and Water Environment Research Center, National Chiao Tung University, 1001 Ta-Hsueh Rd., Hsinchu, Taiwan.

2. TDR PRINCIPLE AND APPRAISAL OF THE HONG KONG METHOD

In the Hong Kong TDR method, a single-core wire is preinstalled alongside the soil-nail rebar, as illustrated in Fig. 1. The rebar and wire form a twin-conductor transmission line, enabling the determination of soil-nail length by TDR (Cheung and Lo 2011). TDR sends an electrical pulse (shown in Fig. 1 is a step pulse) along the transmission line and receives reflections induced by any impedance discontinuities or mismatches. Impedance discontinuities or mismatches in a soil-nail transmission line may be caused by changes in geometry of the conductor configuration or changes in electrical properties of the material in close proximity to the pair of conductors. The characteristic impedance (or just impedance for short) Z of a transmission line is expressed as (Lin and Tang 2007)

$$Z = \frac{Z_p}{\sqrt{\varepsilon}} \tag{1}$$

where Z_p is the geometric impedance defined as the characteristic impedance in free space and ε is the dielectric constant (ε = 1 for air and ε ≈ 10 for cement grout) (Cheung and Lo 2011). In the soil-nail transmission line, the effective dielectric constant is the weighted average of the dielectric constants of both wire plastic sheathing and backfill material. Since the sensing range of the waveguide is mostly focused in the zone in close proximity to the cable and rebar within the grout, the measurement is insensitive to the surrounding soil.

Reflections occur at interfaces of impedance discontinuity, *e.g.*, at the head and end of the soil nail or at the grout-void interface. Both magnitude and polarity of the reflection at any discontinuity interface depend on the contrast of the two impedances on both sides of the interface, which can be expressed in terms of the reflection coefficient

$$\rho = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{2}$$

where Z_1 represents the original impedance and Z_2 is the mismatched impedance of the medium that the pulse is entering into. For a step-pulse input, positive step reflections are induced at the head and end of the soil nail, as shown in Fig. 2, because the soil-nail transmission line has impedance greater than the 50-ohm lead cable and the open end has infinite impedance. In an event of air voids present in the grout, a positive reflection would be returned as the pulse passes from the cement grout to the air void because of an increase in characteristic impedance, whereas a negative reflection would be returned when passing from the air void to the grout. Therefore, the waveform manifests as a hill-shaped curve when the step-pulse passes through any air void sections in the grout annulus, which will be demonstrated in the following experimental results.

The pulse-propagation velocity v_p in the soil nail is also related to the dielectric constant of the propagated medium.

$$v_p = \frac{v_c}{\sqrt{\varepsilon}} \tag{3}$$

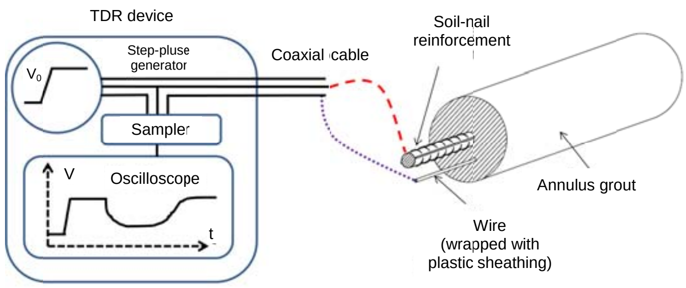

Fig. 1 TDR measurement system for soil-nailing quality control (modified after Cheung and Lo 2011)

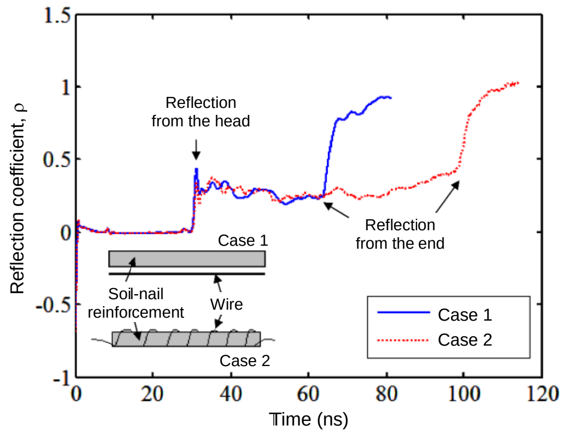

Fig. 2 TDR results on a normal parallel configuration (Case 1) and spiral-wire configuration (Case 2) of soil-nail transmission line

where v_c is speed of light in vacuum (2.998×10^8 m/s). Hence, compared to v_p in cement grout, v_p along the rebar-wire pair is much higher in air voids and much lower in voids filled with water. Two distinct impedance mismatches normally exist at both ends of the soil nail. If v_p is known, the soil-nail length could be estimated from the travel time between the head reflection and the end reflection by

$$L = \frac{v_p T}{2} \tag{4}$$

where L is the distance between the soil-nail head and end and T is the corresponding round-trip travel time.

In the Hong Kong TDR method (Cheung and Lo 2011), a single-core electrical wire was used to couple with the rebar to form a twin-conductor transmission line. The wire may be easily coiled around the rebar; and as a result, the soil-nail length may be unduly overestimated. To demonstrate the case of coiled wire scenario, TDR measurements were conducted on physical models, denoted as Case 1 and Case 2 in Fig. 2. Two rebars of the same length were paired up by a straight and a coiled wire (twice the length of the straight wire), respectively. Measured waveforms show that the travel time is proportional to the wire length, instead of the rebar length. Furthermore, the accuracy of soil-nail length measurement based on total travel time (from soil-nail head to end) depends heavily upon the grout condition. If the grout is intact with no voids, the estimated soil-nailing length would be accurate. However, as the grout becomes defective (*e.g.*, with entrapped air voids), the travel time would decrease since the pulse-propagation velocity (v_p) in air is higher than that in cement grout. Resulted total travel time is a coupled effect of conductor length and pulse-propagation velocity. Reliable determination of soil-nail length is therefore not possible if the pulse-propagation velocity is subjected to change due to the grout condition.

3. NEW TDR SOIL-NAILING WAVEGUIDE CONSTRUCTION AND DATA REDUCTION

A new construction of TDR waveguide is proposed in this study to overcome the aforementioned drawbacks. In the new construction, the single-core wire is replaced by a stiff coaxial cable with an inner conductor and an outer conductor, as shown in Fig. 3(a). The coaxial cable (*e.g.,* Commscope QR320 (CommScope 2014) used in this study) is much stiffer than the single-core wire and cannot be coiled much around the rebar. The coaxial cable alone serves as the waveguide for determination of soil-nail length, as depicted in Fig. 3(b). In this case, the cable length, which is considered equal to the soil-nail length, is obtained reliably and independently of the grout condition since the pulse-propagation velocity of the coaxial cable is fixed by the property of insulating material inside the cable.

After the cable (rebar) length is first determined, a second independent measurement is conducted by utilizing the outer conductor of the coaxial cable together with the rebar to form a sensing waveguide to inspect the grout condition, as depicted in Fig. 3(b). Waveform of the second measurement illustrated in Fig. 3(b) represents the waveform in a soil nail with air void in the middle section of the grout. Grout defect is characterized by an additional hill-shape reflection (indicated in the dotted box) and shorter total travel time (from the head to the end of soil nail). The lumped range of air void in the grout is estimated by travel time relation as follows,

$$\frac{T}{2} = \frac{L_C}{V_C} + \frac{L_S - L_C}{V_{air}} \tag{5}$$

where T is the measured total travel time; L_C is the effective grout length; L_S is the soil-nail length, pre-determined by the previous coaxial cable measurement alone; the term $L_S - L_C$ represents the total length of entrapped voids; V_C is the pulse-propagation velocity in cement grout; V_{air} is the pulse-propagation velocity in air. Cheung and Lo (2011) has shown that the pulse-propagation velocities do not vary significantly with the age of grout (concerning the water content variation), as long as measurements are taken at least one day after grouting. Once the pulse-propagation velocities in cement grout and air (V_C and V_{air}) are determined from some calibration tests, both effective soil-nail length (L_C) and total length of grout loss ($L_S - L_C$) can then be estimated from the measured total travel time using Eq. (5).

The diameter of the coaxial cable used in this study is 1 cm. Although it is about 3 times larger than a single-core wire, the round cable only has a point contact with rebar. Our experience shows that as long as the gap between the rebar and the borehole wall is sufficient, it does not impede the filling of grout. Coaxial cables of smaller diameter can be found and used, but they have smaller allowable bending radius. Too much coiling around the rebar when single- core wires or small coaxial cables are used may significantly reduce the contact area between the rebar and grout. Therefore, using a suitable size of stiff coaxial cable to form the inspection waveguide is desired.

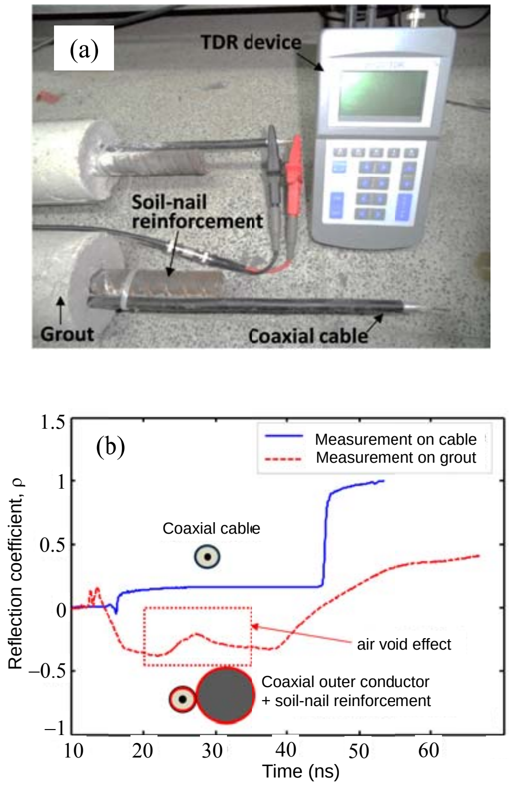

Fig. 3 (a) A photo showing the modified sensing waveguide for quality control of soil-nailing works; (b) The schematic of the waveguide electrodes used for the first measurement on the coaxial cable and the subsequent measurement on the grout

4. LABORATORY EVALUATION OF THE NEW TDR APPROACH

Laboratorial experiments were performed to evaluate the effectiveness of the new approach. As illustrated in Fig. 4(a), three fully-grouted soil nails, 70 cm, 120 cm, and 220 cm in length respectively, were all constructed with Commscope QR320 coaxial cables attached to the rebars. The diameter of the grout cross section is 10 cm. Another 120 cm and 220 cm soil nail were constructed with 55 cm and 70 cm air void respectively, to evaluate the feasibility of the new approach to estimate the effective grout length, as illustrated in Fig. 4(b). In addition, the 220 cm soil nail with 70 cm air void was filled with other different materials, including dry sand (1% water content) and wet sand (20% water content), to investigate effect of different types of grout defects on TDR measurements. Two types of TDR device were used in the laboratory evaluation. The Campbell Scientific TDR100 (Campbell Scientific 2010) produces waveforms

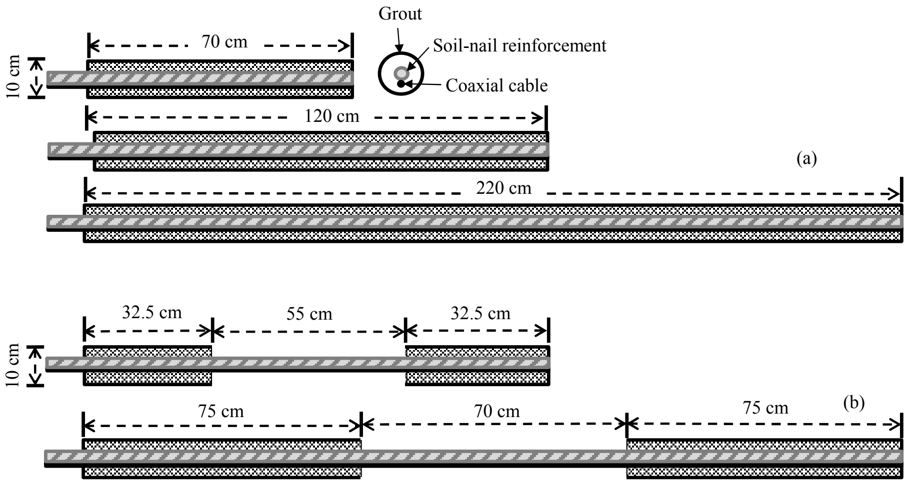

Fig. 4 (a) Three testing configurations of fully-grouted soil nails; (b) Two testing configurations of soil nails with grout defects

with high-speed rise time (≤ 300 ps) and high sampling resolution (minimum 12.2 ps), whereas the portable and low-cost AEA Technology TDR20/20 (AEA Technology 2014) produces waveforms with low-speed rise time (about 4000 ps) and lower sampling resolution (minimum 170 ps). The detail specifications of the TDR devices are listed in Table. 1. Both TDR devices generate a step-pulse rather than an impulse used in Cheung and Lo (2011). Their advantages will be further discussed. Pulse-propagation velocities need to be determined or calibrated beforehand. The pulse-propagation velocity of the QR320 coaxial cable is known from the manufacturer to be 0.87 times the speed of light. By taking measurements on the three rebar-cable pairs of known lengths before and after casting the grout annulus, the pulse-propagation velocities in cement grout and air (V_C and V_{air}) were determined to be 0.48 and 0.88 times the speed of light respectively.

4.1 Inspection of Soil-Nail Length

Figure 5 shows the measured waveforms from the coaxial cables in the fully-grouted soil nails of different length. The measured waveforms from the coaxial cables in the soil nails with grout defects are not shown since they are of the same length as the fully-grouted soil nails. Both TDR100 and TDR20/20 show strong open-end reflections with time delays proportional to the soil-nail length, but only TDR100 clearly depicts the head reflections owing to its sharp rise time. An extra measurement (by short-circuiting the conductors at the soil-nail head) was conducted to give a strong negative reflection at the head, in order to facilitate the determination of travel time, especially for TDR20/20. The points of reflections were quantitatively defined by the dual tangent line method (Chung and Lin 2009). Subsequently, the coaxial cable length, which also represents the soil-nail length, was accurately determined from the pulse travel time between the two reflection signals using Eq. (4). The measured waveforms from the coaxial cables were well behaved and independent of the grout condition, minimizing the potential of operator judgment error. It should be noted that the coaxial cable may not be perfectly straight, but other than that, the new approach eliminated various sources of uncertainties in soil-nail length estimation which were earlier discussed and evaluated by Cheung and Lo (2011).

4.2 Inspection of Soil-Nailing Grout Condition

For each soil nail, a second measurement was then taken using the outer conductor of the coaxial cable and the rebar to form a sensing waveguide for examining the grout condition. As shown in Fig. 6, the waveforms of the second measurements in the grout are more complex than that on the coaxial cable alone, due to the connector to the soil nail and higher heterogeneity in the grout than the insulating material inside the coaxial cable. By comparing the waveforms of fully-grouted soil nails (solid lines) with those with air-void defects (dotted lines), it is shown that air-void defect induces an in-between reflection and reduces the total travel time. However, the ability to "see" the reflection from the air void depends on the void size and the spatial resolution of TDR, which is inversely proportional to the rise time of the incident pulse. Figure 6(a) shows the TDR100 waveform with an apparent hill-shape reflection due to void defect in the grout (similar to the results depicted in Fig.3(a)),while the waveform of low-speed TDR20/20, as shown in Fig. 6(c), does not have an apparent hill-shape reflection to detect the 55 cm void defect in the grout. Nevertheless, all cases in Fig. 6 clearly show reduced travel time from the strong open-end reflection. From the predetermined soil-nail length by the coaxial cable measurement, the effective grout length is estimated from the total travel time using Eq. (5). The results are listed in Table 2. Both TDR100 and TDR20/20 yield satisfactory estimation of effective grout length. Although TDR20/20 produced more dispersive waveforms and did not clearly reveal the reflection signals from relatively small-sized voids, the shortened total travel time due to void existence is reasonably estimated by the dual tangent line method. This finding encouraged the use of low-speed TDR devices for higher portability and cost saving.

Table 1 Specifications of TDR devices for measurement performance

	TDR100*	TDR20/20**
Step-pulse risetime	200 picoseconds	4060 picoseconds***
Timing resolution	Min. 12.2 picoseconds	Min. 169.5 picoseconds
Spatial resolution	1.8 mm	2.54 cm
Measurement range	–2 ~ 2100 m	0 ~ 2010 m

* From Campbell Scientific (2010).
** From AEA Technology (2014).
*** According to the manual, although the TDR20/20 exhibits no dead space, the actual impedance readings in the first 2 feet are indicative rather than absolute. Then the corresponding risetime can be estimated.

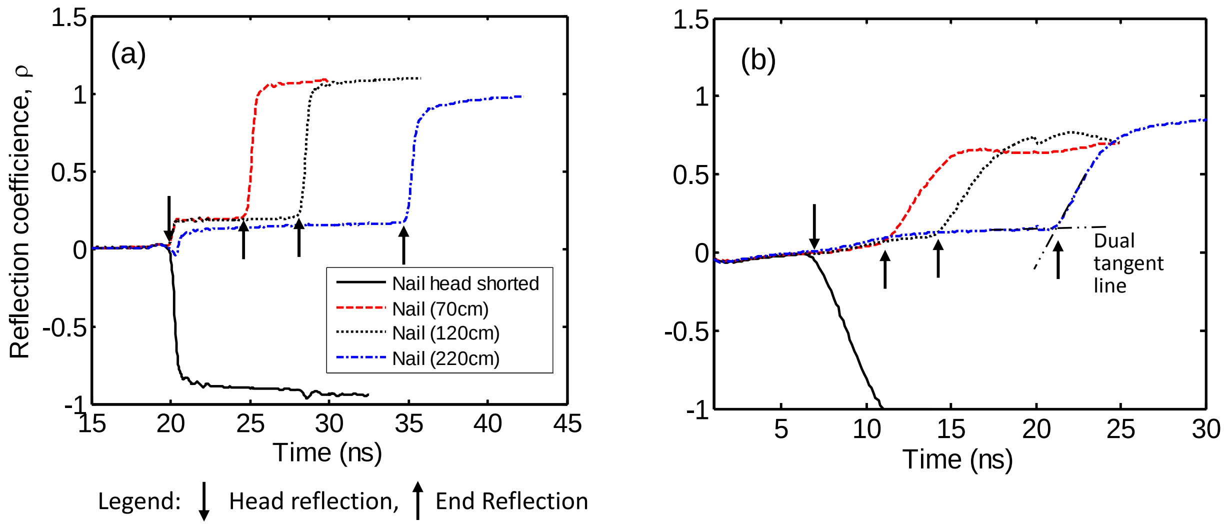

Fig. 5 **Measured TDR waveforms on the coaxial cables in the three soil nails of different length using (a) TDR100 and (b) TDR20/20. The times of head reflections are different because different lead cables were used for the two TDR devices**

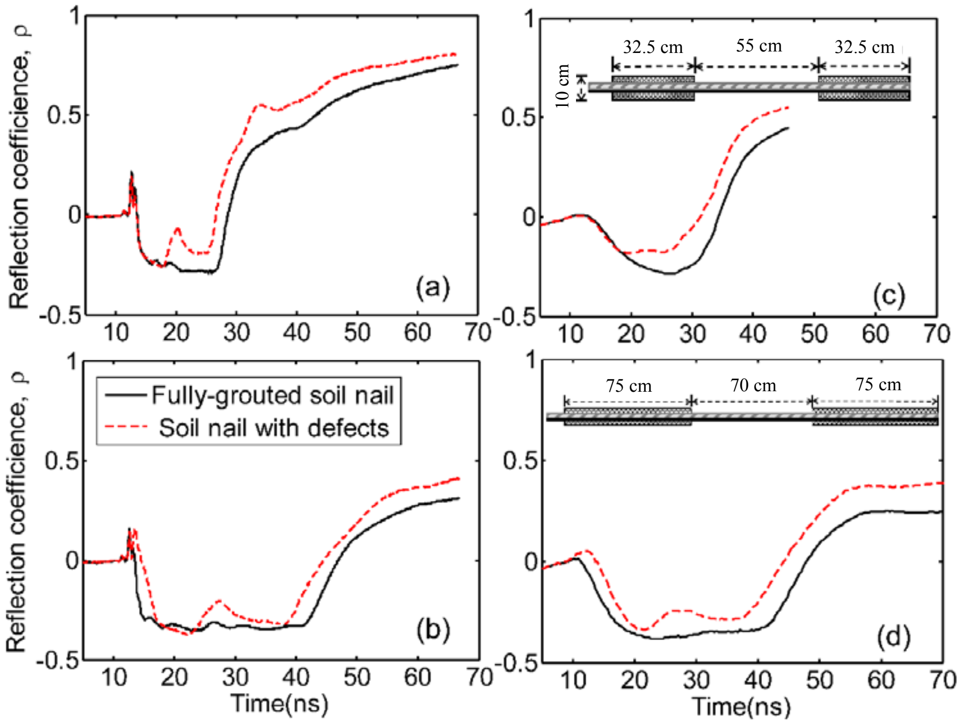

Fig. 6 **Waveforms measured by TDR100 on the grout for (a) the 1.2 m soil nails and (b) 2.2 m soil nails (fully-grouted soil nails in solid lines and soil nails with grout defects in dotted lines). Corresponding results by TDR20/20 are shown in (c) and (d). The location and size of the grout defect are depicted in (c) for the 1.2 m soil nail and in (d) for 2.2 m soil nail**

Table 2 **Estimation of effective grout length from total travel time**

	TDR100		TDR20/20	
	120 cm soil nail with 55 cm grout defect	220 cm soil nail with 70 cm grout defect	120 cm soil nail with 55 cm grout defect	220 cm soil nail with 70 cm grout defect
Estimated effective grout length (cm)	64.3	152.0	68.1	149.5
Accuracy*	98.9%	98.7%	95.2%	99.7%

*** Accuracy =** ***abs*** **(Estimated grout length – Real grout length) / Real grout length**

This study adopted step-pulse TDR devices for the testing. The corresponding impulse responses are obtained by taking derivatives of the waveforms in Fig. 6, as shown in Fig. 7. In comparison with impulse response, step-pulse response eased the identification of reflections from grout defects and determination of travel time by dual tangent line method. On the contrary, when an impulse TDR device is used, the step-pulse response is obtained by taking the integrals of the measured waveform. As a tool for on-site audits, it is recommended to adopt a step-pulse TDR device directly or indirectly convert the waveforms to step-pulse response in the interpretation interface.

4.3 Limitations in Complex Grout Conditions

More complex grout conditions may be encountered in the field. For example, the un-grouted section may be filled with water or mud. The effect of different type of grout defects was examined by filling the void with dry sand (water content ω = 1%) and wet sand (ω = 20%). The resulting waveforms are shown in Fig. 8. The dielectric constant of dry sand section is only slightly higher than that of air void. Therefore, their measured waveforms are quite similar. On the contrary, the wet sand section has a higher dielectric constant, resulting in lower characteristic impedance (Eq. 1) and lower propagation velocity (Eq. 3). According to the measured waveforms in Fig. 8, the dielectric constant of the wet sand section seems slightly higher than that of intact grout. In the defect section, there appeared to be a negative reflection (a concave response) followed by a positive reflection. Two subsequent positive reflections from the soil-grout interface and open end often make the open-end reflection less clear for travel time analysis. In rare condition, when the moisture content of the entrapped soil in the gout is such that the effective dielectric constant is the same as the intact grout, it would not be possible to identify the grout defect. However, engineers are most concerned about void defects associated with loss of pulled out resistance.

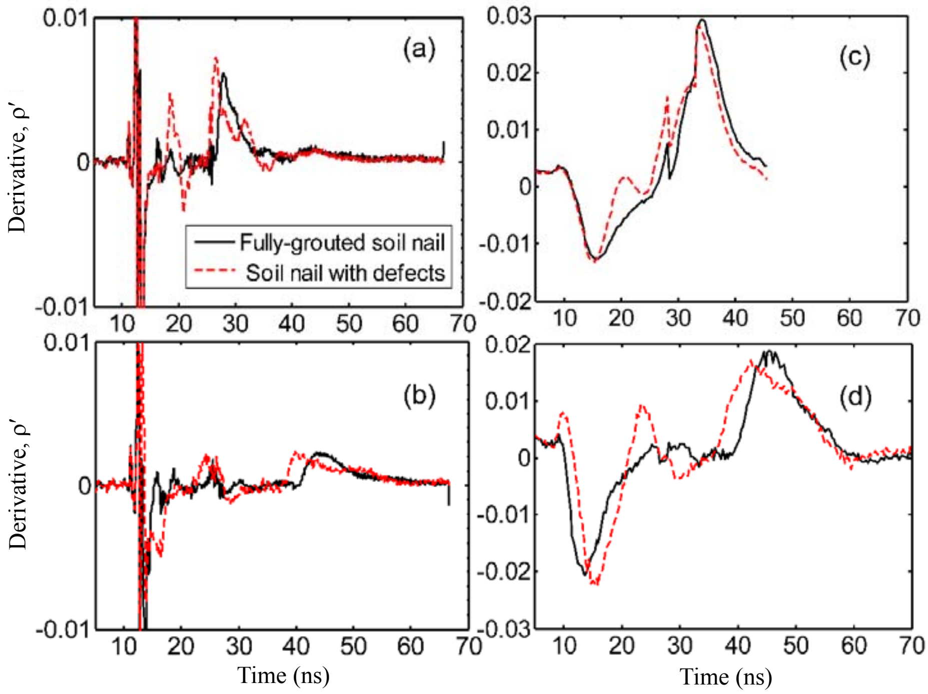

Fig. 7 The derivative of waveforms shown in Fig. 6

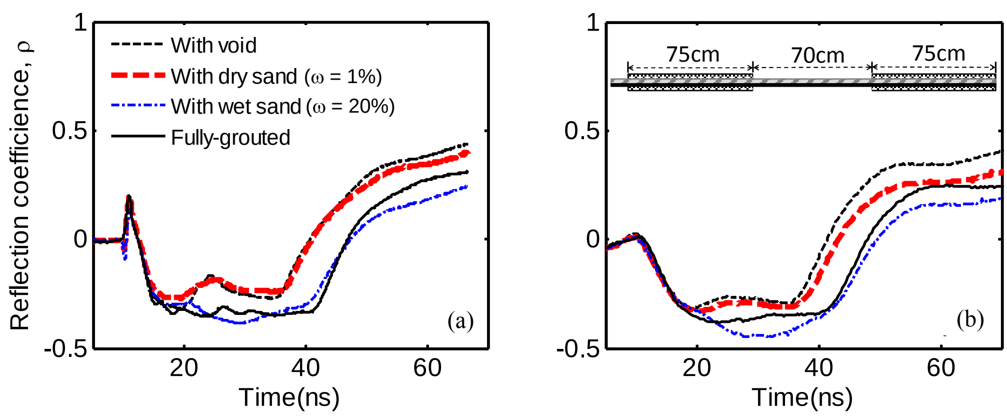

Fig. 8 Measured TDR waveforms on the soil nail with different types of filling defects using (a) TDR100 and (b) TDR20/20

The velocity for the ($L_S - L_C$) term in Eq. (5) is no longer equal to V_{air} if the grout defect is not a simple air void. One should come up with a representative velocity for the defected section in order to estimate the effective grout length using Eq. (5). Since the condition of the grout defect is not known a priori, it is not possible to calibrate the velocity beforehand. Detailed analysis in complex grout conditions requires full waveform analysis based on the comprehensive wave propagation model developed for TDR measurement system (Lin and Tang 2007). However, further study is needed to develop a repeatable testing connector and full waveform inversion.

5. SUMMARY AND CONCLUSIONS

Two drawbacks of current TDR practice for inspecting soil-nailing works were identified: (1) Single-core electrical wire could be easily coiled around the rebar, leading to excessive overestimation of TDR-deduced soil-nail length; (2) Determination of soil-nail length may be unreliable if the grout annulus is irregular or defective. This study further introduced a new TDR soil-nail waveguide construction and de-coupled data reduction, in order to overcome these issues and eliminate almost all uncertainties previously identified. The new approach changes how TDR method is practiced for inspecting soil-nailing works in four aspects, including construction of soil-nail waveguide, presentation of TDR waveform (*i.e.,* step response *vs.* pulse response), analysis of TDR waveform, and selection of appropriate TDR devices.

The sensing waveguide is formed by attaching a stiff coaxial cable alongside the rebar to form a novel dual-functional waveguide. The stiff coaxial cable, which avoids excessive coiling and span similarly to the rebar, is used to pulse the soil-nail length independent of grout condition. The outer conductor of the coaxial cable and the rebar forms another waveguide for grout condition sensing. Void sections in the grout would induce additional reflections in TDR waveforms and change the total travel time from the head to the end of soil nail. Void detection requires a high-speed TDR device, but this requirement may be largely relaxed by the proposed data reduction method based on total travel time. With the soil-nail length predetermined by an independent measurement on the coaxial cable, the effective grout length was shown to be reasonably estimated from the measured total travel time of the strong reflections from head and end of soil nail. Therefore, a portable, low-cost, and low-speed TDR device suffices for such a task. Moreover, a step-pulse TDR was shown to possess apparent advantages over a short-pulse TDR during waveform interpretation. More complex grout conditions may be encountered in the field. Further study based on full waveform analysis is needed if detailed examination of grout condition is desired.

REFERENCES

AEA Technology (2014). "Time Domain Reflectometer (TDR): E20/20 TDR." http://www.aeatechnology.com/products/tdr/2020tdr.

Campbell Scientific (2010). *TDR100 Instruction Manual*. Campbell Scientific, Inc.

Chan, R.K.S. (2008). *Guide to Soil Nail Design and Construction*, Geoguide 7, Geotechnical Engineering Office, Hong Kong.

Cheung, W.M. (2003). "Non-destructive tests for determining the lengths of installed steel soil nails." *GEO Rep. No. 133*, Civil Engineering and Development Dept., Geotechnical Engineering Office, Hong Kong.

Cheung, W.M. and Lo, D.O.K. (2005). "Interim report on non- destructive tests for checking the integrity of cement grout sleeve of installed soil nails." *GEO Rep. No. 176*, Civil Engineering and Development Dept., Geotechnical Engineering Office, Hong Kong.

Cheung, W.M. (2006). "Use of time domain reflectometry to determine the length of steel soil nails with pre-installed wires." *GEO Rep. No. 198*, Civil Engineering and Development Dept., Geotechnical Engineering Office, Hong Kong.

Cheung, W.M. and Lo, D.O.K. (2011). "Use of time-domain reflectometry for quality control of soil-nailing works." *Journal of Geotechnical and Geoenvironmental Engineering*, **137**(12), 1222−1235.

Chung, C.-C. and Lin, C.-P. (2009). "Apparent dielectric constant and effective frequency of TDR measurements: Influencing factors and comparison." *Vadose Zone Journal*, **8**(3), 548−556.

CommScope (2014). "QR® 320 JCA", http://www.commscope.com/catalog/broadband/2147483659/product_details.aspx?id=47071.

Lee, C.F. and Ove Arup & Partners Hong Kong Limited (OAP) (2007). "Review of use of non-destructive testing in quality control in soil nailing works." *GEO Rep. No. 219*, Civil Engineering and Development Dept., Geotechnical Engineering Office, Hong Kong.

Lin, C.-P. and Tang, S.-H. (2007). "Comprehensive wave propagation model to improve TDR interpretations for geotechnical applications." *Geotechnical Testing Journal*, **30**(2), 90–97.

Zostrich Geotechnical (2016). "TDR verified rock bolt and soil nail length." http://www.zostrich.com/Monitoring_PDF/tdr_bolt_length.pdf (2016/05/16).