Technical Note

Improved TDR Method for Quality Control of Soil-Nailing Works

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Abstract: Time domain reflectometry (TDR) has become an effective nondestructive testing method for soil-nailing inspection. Previous studies utilized a preinstalled, single-core, electric wire alongside the rebar within the soil nail. Measurements may be affected by possible grout defects and excessively overestimate the rebar length if the wire is coiled around the rebar. An improved TDR waveguide and a corresponding decoupled data reduction method (for both soil-nail length determination and grout condition inspection) are proposed herein. The feasibility and advantages of the new approach were experimentally verified with two types of TDR device. The proposed methodology makes it possible to use a portable, low-cost, and low-speed TDR device as a quick and economical tool for quality control of soil nailing.
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Introduction

Soil nailing is an effective, cost-effective, and widely used technique for enhancing 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 overall strength of a soil-nailing system. However, thorough supervision at all times during construction stage is not possible. Nondestructive testing (NDT) methods are desirable to provide quick inspection of installed soil nails and allow independent site audits. Numerous NDT methods, including sonic echo, mise-a-la-masse, electromagnetic induction, 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 OAP 2007). Among these NDT methods, TDR was found to be the most effective in these studies (but may not be for a range of field conditions) based on a large number of field measurements and a pilot quality assurance program (Lee and OAP 2007).

The TDR method for quality inspection of soil-nailing works involves pre-installing a single-core electrical wire alongside the soil-nail rebar to form a twin-conductor transmission line for TDR measurement. The corresponding guidelines on TDR testing procedure and interpretation of test results can be found in Cheung (2006). Cheung and Lo (2011) further examined various uncertainties in soil-nail length estimation using TDR. However, current TDR method may be affected by possible grout defects and excessively overestimates the rebar length if the wire is coiled around the rebar. To overcome these problems, this study introduced an innovative waveguide and data reduction method for enhancing the reliability of soil-nail length determination while providing independent cement grout quality assessment at the same time.

New Dual-Function Soil-Nail Waveguide and Test Program

A new TDR waveguide for soil-nailing inspection is proposed in this study to overcome the aforementioned drawbacks. The single-core wire is replaced by a stiff coaxial cable with an inner conductor and an outer conductor to form two independent sensing waveguides for soil-nail length determination and inspection of grout condition, respectively. The coaxial cable [e.g., Commscope QR320 (CommScope 2014) used in this study] is much stiffer and cannot be coiled much around the rebar. The coaxial cable alone serves as the waveguide for determination of soil-nail length. As the pulse-propagation velocity of the coaxial cable is fixed by the properties of insulating material inside the cable, the cable length which is considered to be equal to the soil-nail length, is obtained reliably from the round-trip total travel time between the strong head reflection and the end reflection and independently of the grout condition.

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 another sensing waveguide to inspect the grout condition. Both the pulse-propagation velocity and characteristic impedance depend on the dielectric constant of the propagated medium surrounding the conductors. In an event of air voids present within the grout annulus, 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. Thus, grout defect is characterized by an additional hill-shape reflection and shorter travel time (from the soil-nail head to its end) compared with the intact grout. The range of air void in the grout may be further quantitatively

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estimated based on travel time information and known soil-nail length determined in the first measurement.

To evaluate the effectiveness of the new approach, a laboratory test program was designed. Three fully-grouted soil nails, 70, 120, 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 set of 120 and 220-cm soil nails were constructed with 55 and 70-cm air void, respectively, for evaluating the feasibility of the new approach to inspect grout condition and estimate the effective grout length. Two types of TDR device were adopted in this study. The Campbell Scientific TDR 100 (Campbell Scientific 2010) produces waveforms with high-speed rise time (≤300 ps) and high sampling resolution (minimum 12.2 ps), whereas the portable and low-cost AEA Technology TDR 20/20 (AEA Technology 2014) produces waveforms with low-speed rise time (about 4,000 ps) and lower sampling resolution (minimum 170 ps). Both TDR devices generate an EM step pulse rather than a short pulse used in Cheung and Lo (2011), the advantages of which are elaborated in further context.

Results and Analysis

Determination of Soil-Nail Length

Fig. 1 shows the measured waveforms from the coaxial cables in the soil nails of different length. Both TDR100 and TDR20/20 showed 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 TDR 20/20. The reflection points were quantitatively defined by the dual tangent line method, which provides precise travel time estimation (Chung and Lin 2009). The pulse-propagation velocity of the QR320 coaxial cable is known from the manufacturer to be 0.87 times the speed of light. Subsequently, the coaxial cable length, which also represented the soil-nail length, was accurately determined from the pulse travel time. The measured waveforms from the coaxial cables are well behaved and independent of the grout condition, minimizing the risk of operator judgment error. It should be noted that the coaxial cable may not be perfectly straight, but other than that, the modified approach eliminated various sources of uncertainties in soil-nail length estimation which were earlier discussed and evaluated by Cheung and Lo (2011).

Quantitative Inspection of Grout Condition

For each soil nail, a second measurement was then taken using the outer conductor of the coaxial cable and the rebar, in order to form a sensing waveguide for examining the grout condition. As an example, the results of the 1.2 m soil nail are shown in Fig. 2. By comparing the waveforms of the fully-grouted soil nail (solid lines) to the one with grout defect (dotted lines) in Fig. 2(a), it is shown that air-void defect induced an in-between hill-shape reflection and reduced the total travel time in the TDR 100 response. 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 EM step pulse. Fig. 2(b) shows that the low-speed TDR 20/20 was unable to detect the 55-cm void simply from the waveform. Nevertheless, both Figs. 2(a and b) clearly show reduced travel time from the strong open-end reflection.

From the predetermined soil-nail length by the coaxial cable measurement, it is possible to estimate the range of air void quantitatively or contrarily the effective grout length, even without "seeing" the void reflection in the waveform. The round-trip total travel time of the TDR pulse from the soil-nail head to its end can be derived as

$$T = 2\left(\frac{L_C}{V_C} + \frac{L_S - L_C}{V_{\mathrm{air}}}\right) \tag{1}$$

where T = round-trip travel time from the soil-nail head to its end; L_C = effective grout length; L_S = soil-nail length, which is pre-determined separately by the previous coaxial cable measurement; the term $L_S - L_C$ = total length of entrapped voids; V_C = pulse-propagation velocity in cement grout; and V_{air} = pulse-propagation velocity in air. 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 ($L_S - L_C$) are then estimated from the measured total travel time using Eq. (1). 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. The effective grout lengths of the defective soil nails were estimated from the total travel time using Eq. (1). The results are listed in Table 1. Both TDR 100 and TDR 20/20 yield satisfactory estimation of effective grout length (Accuracy > 95%). Although TDR 20/20 produced more dispersive waveforms and did not clearly reveal the reflection signals from relatively small-sized

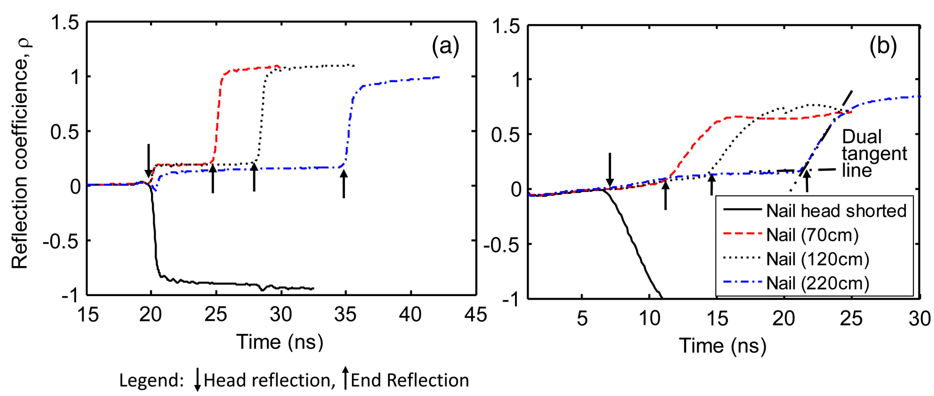

Fig. 1. Measured TDR waveforms on the coaxial cables in the three soil nails of different length using (a) TDR 100; (b) TDR 20/20

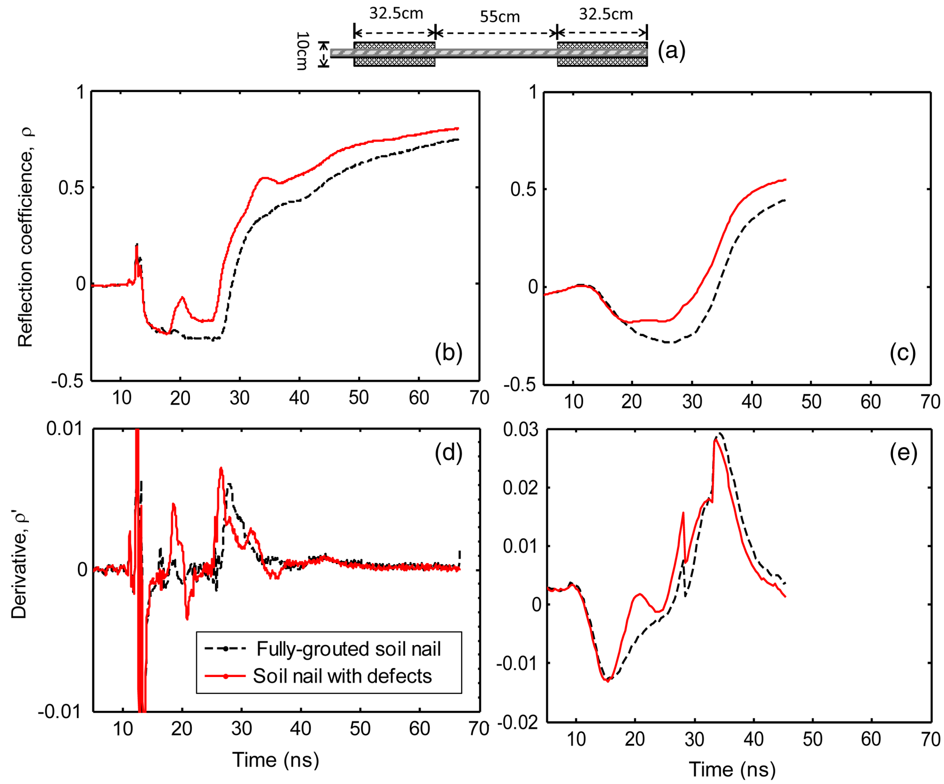

Fig. 2. Waveforms of the (a) 1.2-m soil nails with 55 cm defect measured by (b) TDR 100 and (c) TDR 20/20 (fully-grouted soil nails in dotted lines and soil nails with grout defects in solid lines). Corresponding derivative of waveforms are shown in (d) and (e)

Table 1. Estimation of Effective Grout Length from Total Travel Time

	TDR100		TDR20/20	
Testing groups	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[a] (%)	98.9	98.7	95.2	99.7

[a]Accuracy = *abs* (estimated grout length–real grout length)/real grout length.

voids, the shorter total travel time (due to void existence) was reasonably estimated by the dual tangent line method. This finding encourages the use of low-speed TDR devices for higher portability and cost saving.

Short-Pulse versus Step-Pulse Responses

Instead of the short-pulse TDR device used in Cheung and Lo (2011) and reports of the Hong Kong method, this study adopted two step-pulse TDR devices in laboratorial testing. The corresponding short-pulse responses were obtained from the derivative of the waveforms in Figs. 2(a and b), as shown in Figs. 2(c and d). In comparison to short-pulse response, step-pulse response eased the identification of reflections from grout defects and the determination of travel time by dual tangent line method. On the contrary, when a short-pulse TDR device is used, the step-pulse response can be obtained by taking the integral of the measured waveform. From the comparison between the step-pulse responses and short-pulse responses, it is recommended to adopt a step-pulse TDR device directly or indirectly convert the short-pulse waveforms to step-pulse response in the interpretation interface.

Summary and Conclusions

The proposed TDR method may improve soil-nailing inspection by:

1. Constructing a novel dual-function waveguide using appropriate stiff coaxial cable to avoid excessive coiling around the rebar and allow two decoupled measurements for soil-nail length determination and grout inspection using the inner and outer conductor, respectively;
2. Presenting the TDR waveform as a step pulse response for better identification of grout defects and determination of travel time by dual tangent line method;
3. Quantitatively estimating the effective grout length from the reduced total travel time between the strong head reflection and the end reflection; and

4. Allowing the use of a portable, low-cost, and low-speed TDR device by the two decoupled measurements and data reduction based on total travel time.

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