Use of Time Domain Reflectometry (TDR) with Pre-installed Wires to Check the Grout Integrity of Soil Nails

GEO Report No. 304

C.S.C. Tang & P.F.K. Cheng

Geotechnical Engineering Office
Civil Engineering and Development Department
The Government of the Hong Kong
Special Administrative Region

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Preface

In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. The GEO Reports can be downloaded from the website of the Civil Engineering and Development Department (http://www.cedd.gov.hk) on the Internet. Printed copies are also available for some GEO Reports. For printed copies, a charge is made to cover the cost of printing.

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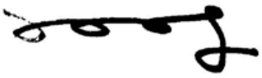

H.N. Wong
Head, Geotechnical Engineering Office
December 2014

Foreword

This report presents a study on the application of Time Domain Reflectometry (TDR) to identify defects in the cement grout sleeves of soil nails. Prefabricated soil nails with known voids in the grout sleeves were tested in the study.

This report was prepared by Ir Patty F.K. Cheng & Ir Chris S.C. Tang of the Standards and Testing Division under the supervision of Ir Alan C.W. Wong. The study was initiated by Dr Raymond W.M. Cheung. The Drafting Unit of the Standards and Testing Division, in particular Mr Stephen M.K. Lo and Mr Harold C.K. Lee, assisted in the preparation of this report. Many GEO colleagues gave useful comments on the draft version of the report. All contributions are gratefully acknowledged.

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Abstract

As part of the development work on non-destructive tests for quality control of soil nails, GEO carried out a study on the application of Time Domain Reflectometry (TDR) to identify defects in the cement grout sleeve of soil nails. This application makes use of the disparities in pulse propagation velocities and waveforms resulting from the presence of grout defects in soil nails.

Soil nails with built-in grout defects were prefabricated for the study. TDR tests were conducted on these prefabricated nails, with an aim to examining how the TDR test results correlate with the presence of built-in grout defects. A case study is also presented to illustrate how TDR could be used to identify installed soil nails with significant grout defects.

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1 Introduction

Time Domain Reflectometry (TDR) is an effective non-destructive tool for determining the length of installed soil nails with pre-installed conducting wires (Cheung, 2003). The Geotechnical Engineering Office (GEO) has been implementing a quality assurance framework by adopting this technique since 2004 under the Landslip Preventive Measures (LPM) Programme and the succeeding Landslip Prevention and Mitigation (LPMit) Programme. This quality assurance framework for soil nailing works is also used in works projects of the other works departments, such as Highways Department and Water Supplies Department.

In 2005, the GEO conducted a review of non-destructive methods for checking the integrity of cement grout sleeve of soil nails (Cheung & Lo, 2005). The review identified five feasible methods which, however, did not include TDR with pre-installed wires.

The GEO subsequently carried out a study on the use of TDR with pre-installed wires for checking the integrity of cement grout sleeve of soil nails. Soil nails with purposely built-in grout defects in the form of discontinuities in the grout sleeves were prefabricated, and tested by using the TDR technique. The TDR waveforms recorded at these prefabricated soil nails were examined.

Some of the results of the study have been published in technical papers by Pun et al (2008), Lo & Cheung (2011) and Cheung & Lo (2011).

This report presents the findings of the study and documents a case history involving the use of TDR for detection of significant grout defects in installed soil nails. The principles of the TDR and its application for checking grout integrity are also discussed.

2 Assessment of the Integrity of Grouted Soil Nails

2.1 Applications of TDR Technique

TDR is a widely adopted method for detecting cable faults in telecommunication industry. Its application has been extended to geotechnical engineering, in areas such as identification of slip plane in slope movement, detection of groundwater level and determination of soil moisture content (O'Connor & Dowding, 1999; Siddiqui et al, 2000). Other areas of application include using TDR with pre-installed sensor wires to detect the location and size of void in grouted post-tensioned bridges (Chajes et al, 2003; Li et al, 2005). The technique of TDR has been applied for measuring soil nail length since mid-2004.

2.2 Principles of TDR for Checking Grout Integrity

The TDR method involves sending an electrical pulse through a pair of conductors and observing the reflected pulse caused by a discontinuity. The time elapsed is used to determine the location of the discontinuity. When applied in soil nails, the reinforcement bar together with the pre-installed wire is analogous to the conductor pair (Cheung, 2003).

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In theory, the pulse propagation velocity, v_p, is related to the electrical properties of the material in the close proximity to the pair of conductors by the following expression (Topp et al, 1980):

$$v_p = \frac{v_c}{\sqrt{\varepsilon}} \qquad (2.1)$$

In Equation 2.1, v_c is the speed of light in vacuum ($3x10^8$ m/s) and ε is the dielectric constant of the medium, which is a measure of how a material reacts when it is subject to a steady-state electric field. The typical values of ε for air and cement grout are 1 and 10 respectively. As shown in Equation 2.1, the pulse propagation velocity in lower dielectric materials would be increased at a rate which is in proportion to the inverse of the square root of the dielectric constant. As a result, the pulse propagation velocity in air (being a lower dielectric material) would be higher when compared with that in cement grout.

In order to verify the above, three test soil nails of equal lengths embedded in air, soil and cement grout respectively were assembled in the Public Works Laboratories, and their TDR test waveforms were examined (see Figure 2.1). It is observed that pulse propagation velocity in air is faster than that in soil, which is in turn faster than that in cement grout. These differences in pulse propagation velocity enable the identification of soil nails with voids in the grout sleeves.

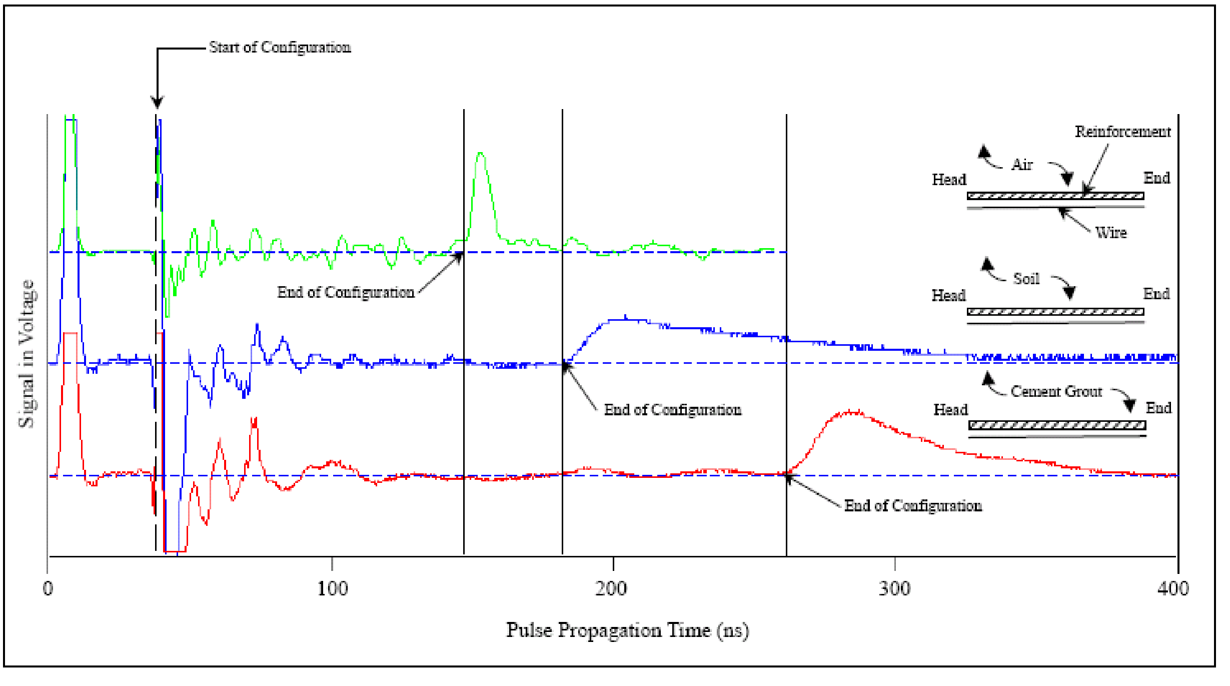

Figure 2.1 TDR Pulse Propagation Velocity in Different Embedding Materials

Apart from the difference in pulse propagation velocity, anomalous TDR waveform is also an indication of the presence of significant grout defects (i.e. voids in the grout sleeves). A discontinuity in a grout sleeve is associated with a change in electrical impedance, i.e. grout verses air. A pulse reflection would be induced when there is a change in electrical

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impedance along a transmission line. The polarity of a reflected pulse (i.e. positive or negative) is related to the reflection coefficient, Γ (Hewlett Packard, 1998), which can be expressed as:

$$\Gamma = \frac{V_r}{V_i} = \frac{Z - Z_o}{Z + Z_o} \quad \text{....................} \quad (2.2)$$

where V_r = the peak voltage of the reflected pulse
V_i = the peak voltage of the incident pulse
Z = the electrical impedance at the point of reflection
Z_o = the characteristic electrical impedance of the reinforcement-wire pair

Based on Equation 2.2, the polarity of Γ depends on the magnitude of Z relative to that of Z_o. For example, when a pulse travels along a grouted reinforcement-wire configuration with intermittent void section, a positive pulse reflection (as indicated by a positive Γ) will occur when the pulse passes the grout-void interface since Z(grout) = Z_o < Z(void). On the other hand, when the pulse re-enters the grouted configuration from the void section, a negative pulse reflection (as indicated by a negative Γ) will occur since Z(void) = Z_o > Z(grout). This phenomenon is illustrated in Figure 2.2.

For a soil nail with a grout defect (void) at the nail end, a positive reflection would be returned when the transmission wave arrives at the grout to void interface (increase in impedance), followed by a positive reflection at the end of the reinforcement-wire pair (Figure 2.3).

For a soil nail with a grout defect (void) at the head, a negative reflection is returned at the void to grout interface (decrease in impedance), followed by a positive reflection at the end of the nail (Figure 2.4).

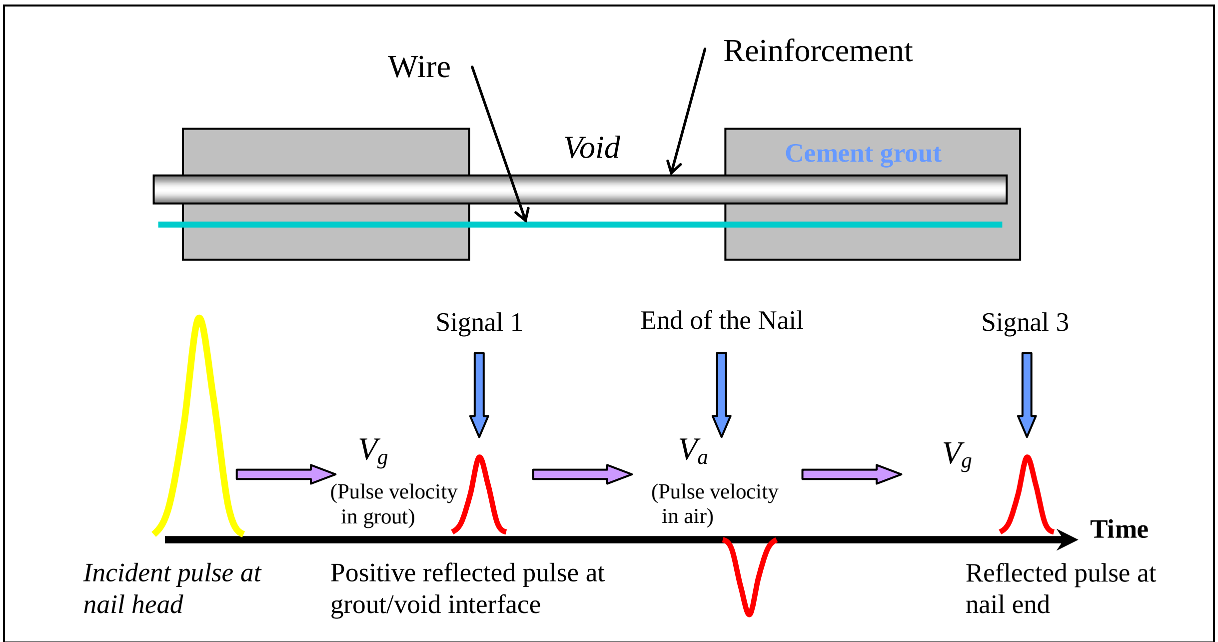

Figure 2.2 Reflected Pulses of a Soil Nail with Grout Defects

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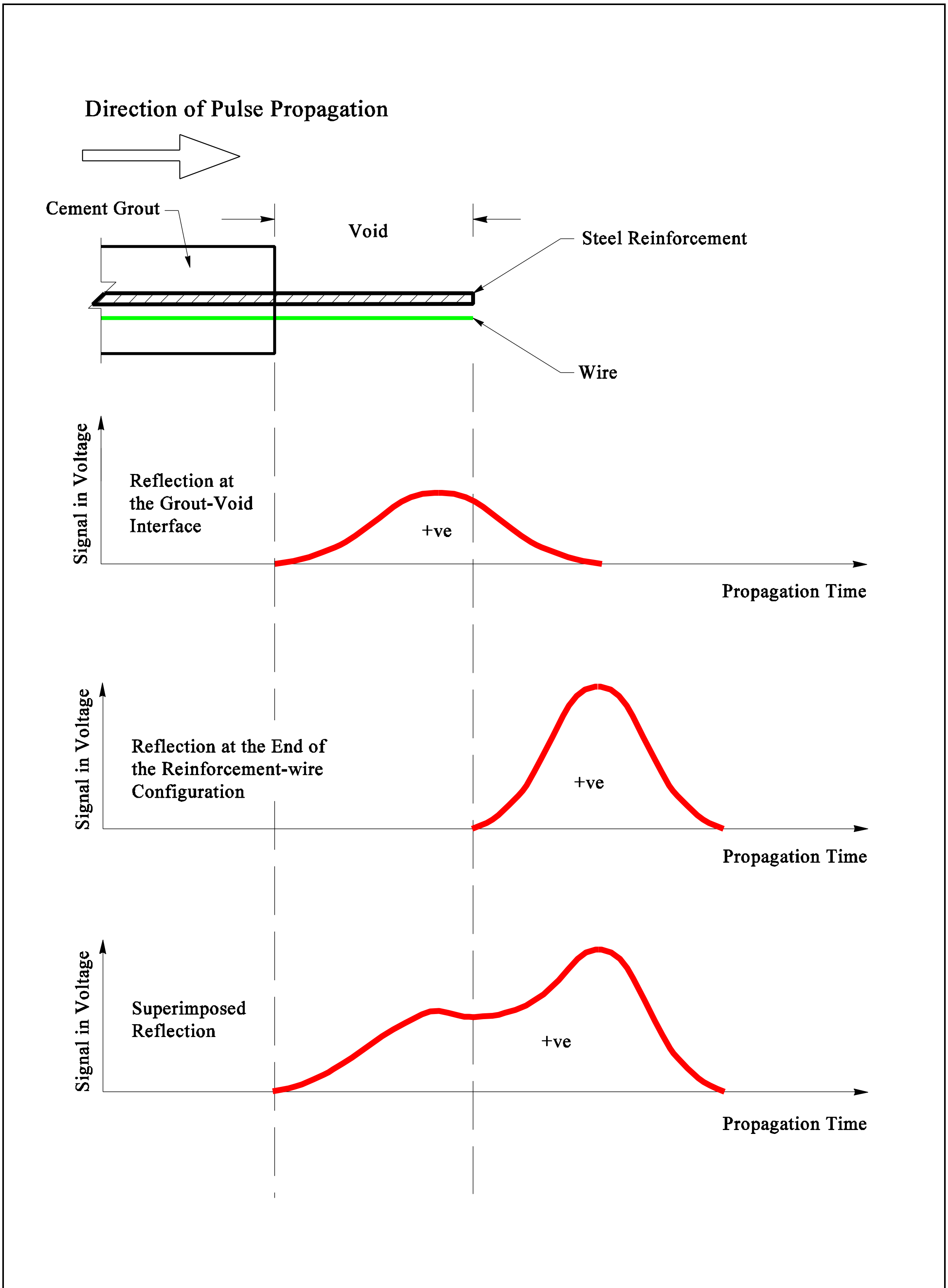

Figure 2.3 Waveform of a Soil Nail with Grout Defects at the Nail End

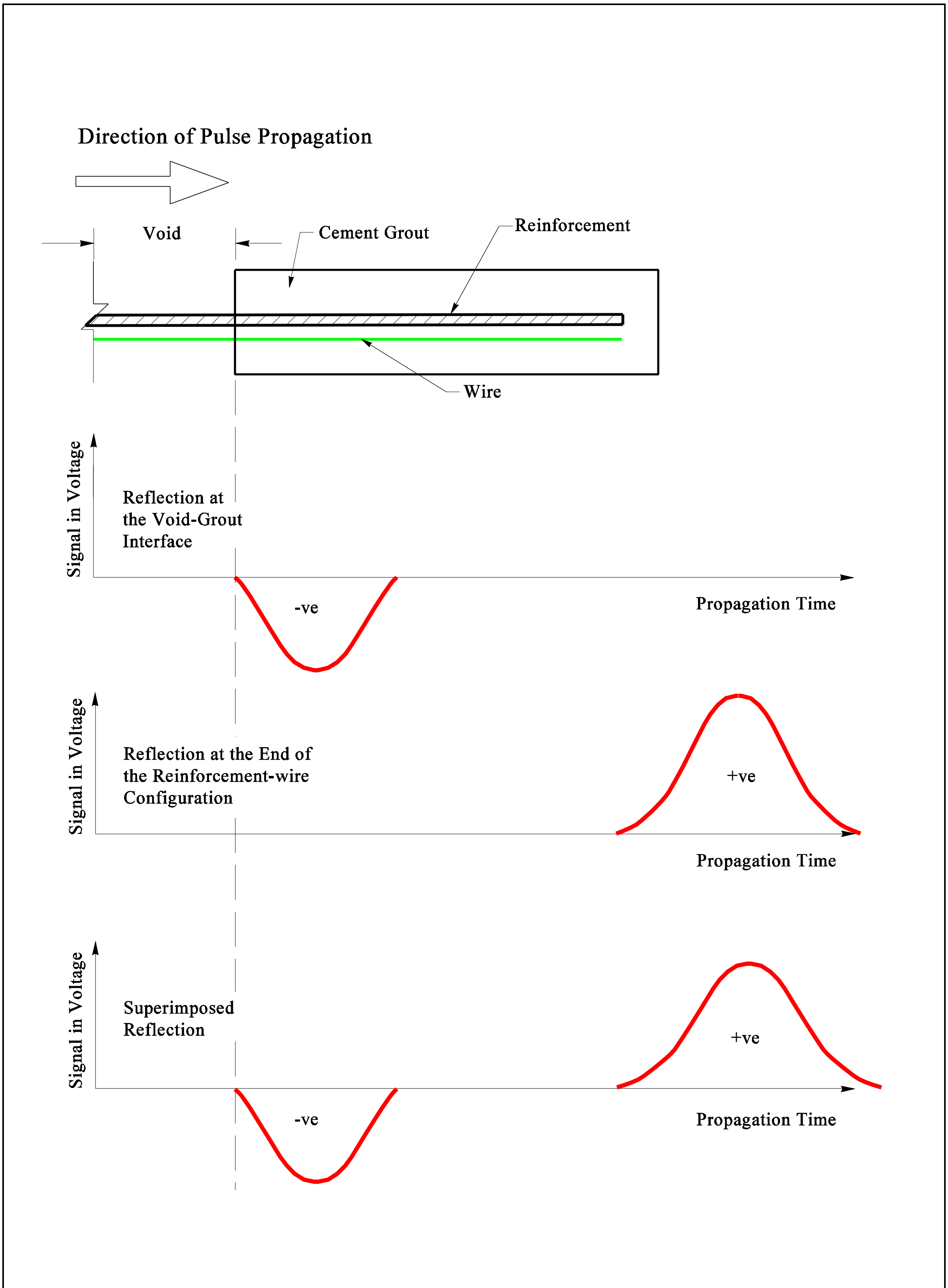

Figure 2.4 Waveform of a Soil Nail with Grout Defect at the Nail Head

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The waveform of a soil nail with an intermediate grout defect (void) is illustrated in Figure 2.5. A positive reflection would be returned when the pulse leaves the grout (increase in impedance). A negative reflection would be returned when the pulse re-enters the grout (decrease in impedance).

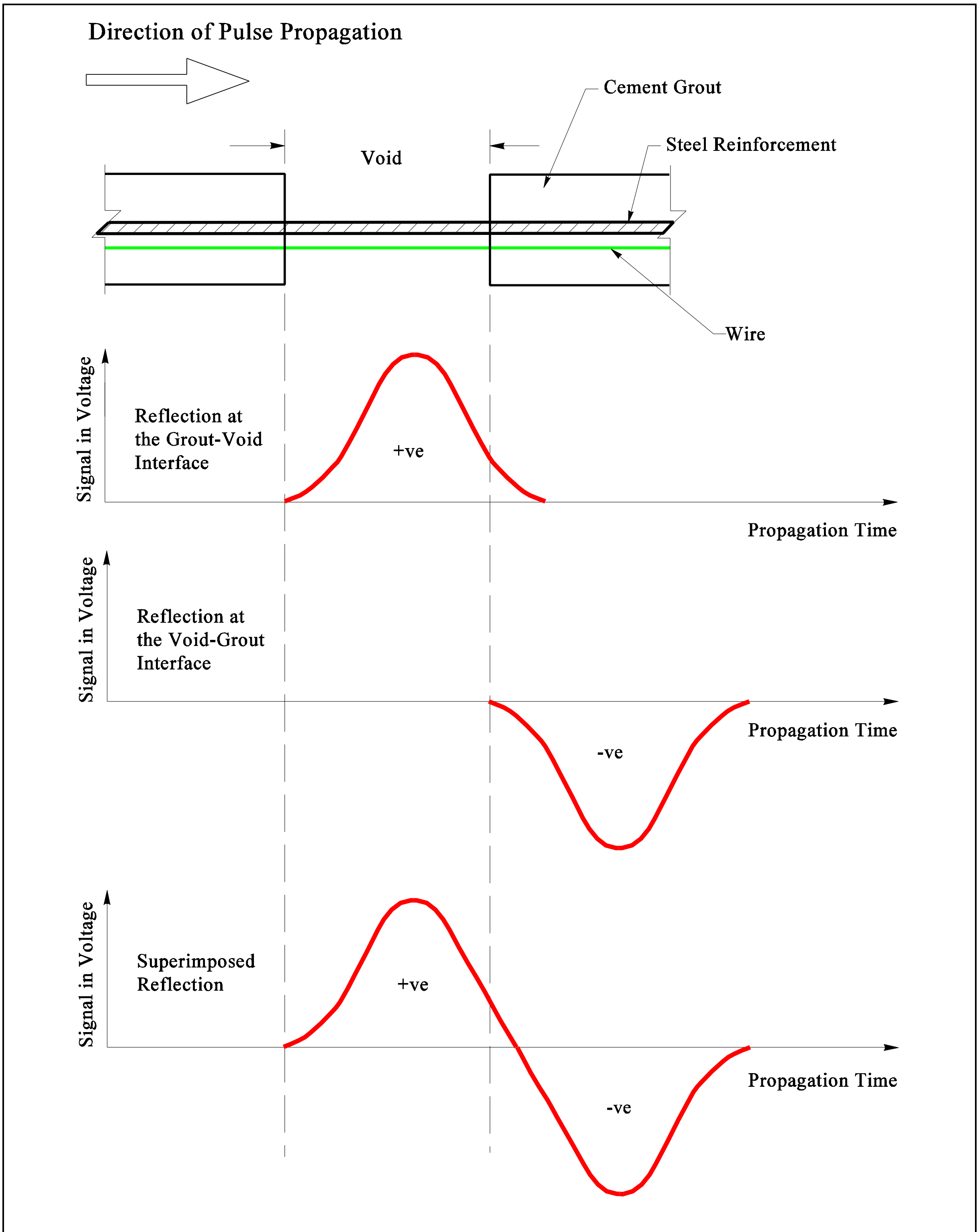

Figure 2.5 Waveform of a Soil Nail with a Void between Cement Grout

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2.3 Other Factors Affecting Interpretation of TDR Results

The influences of other factors, such as the medium surrounding the cement grout sleeve of soil nails and the presence of couplers, on the identification of grout defects have been studied. The results are presented in the following sections.

2.3.1 Effect of Medium Surrounding a Soil Nail

To study whether the materials surrounding the cement grout sleeve of a soil nail will affect the TDR results, a soil nail with a 100 mm diameter cement grout sleeve was prefabricated. TDR measurements were taken when the soil nail was exposed in air and after it had been buried in soil. The resultant waveforms obtained from both cases are shown together in Figure 2.6.

The results suggest that the materials surrounding the cement grout sleeve of a soil nail have no significant effect on the TDR pulse propagation velocity and the waveform.

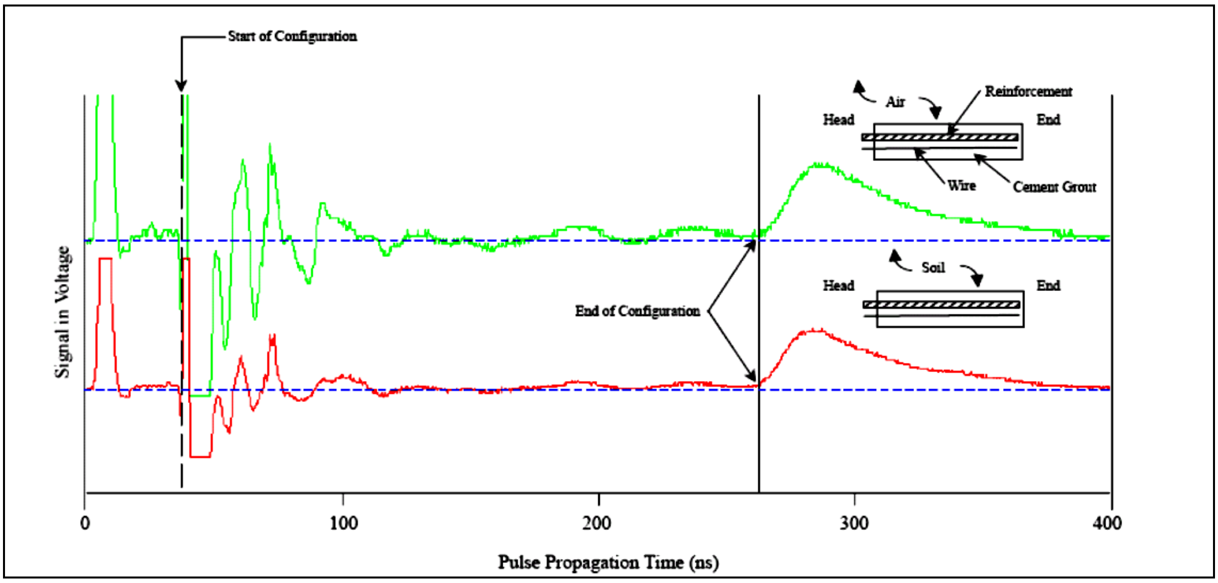

Figure 2.6 Effect of Materials Surrounding the Cement Grout Sleeve of a Soil Nail

2.3.2 Effect of Couplers

There is a concern that the wave reflection due to the change in impedance resulting from installation of couplers in a soil nail may affect the wave propagation velocity and waveform of a TDR test. To examine such effects, a review of the TDR waveforms obtained from two control soil nails with the same length, one with a coupler and the other without a coupler, was carried out. Figure 2.7 shows the comparison of TDR waveforms obtained from these two test soil nails. The upper waveform was recorded from the soil nail without the coupler whereas the lower waveform was the one with a coupler. It is noted that no significant reflection was returned at the location of the coupler.

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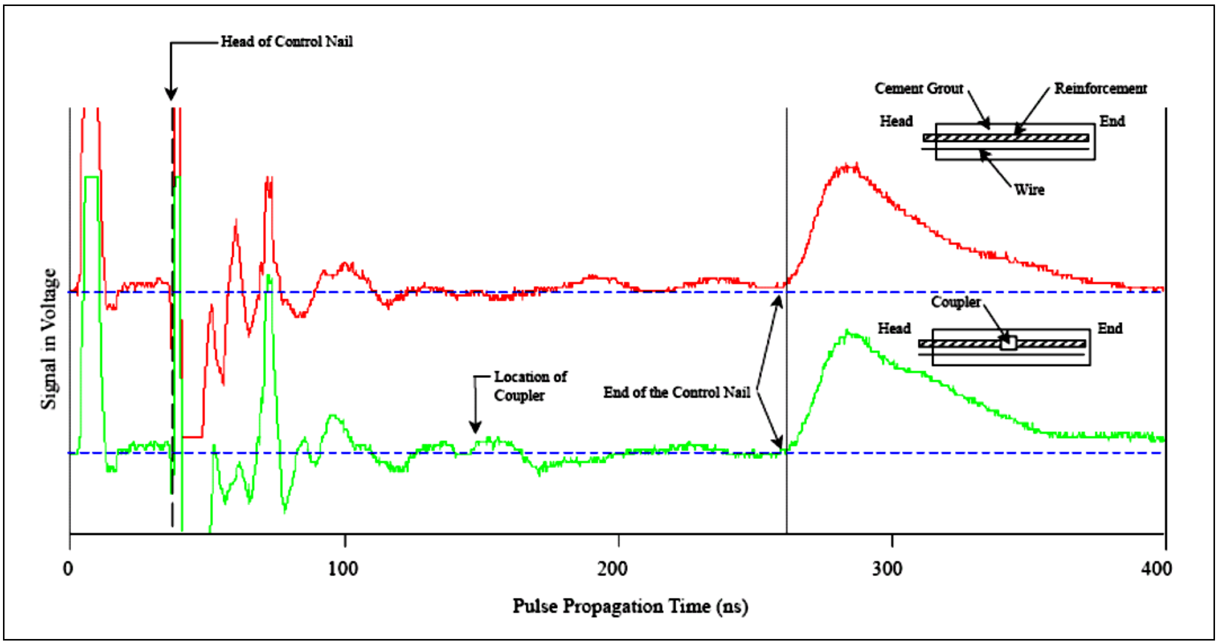

Figure 2.7 Effect of Coupler on the Waveforms of Control Nails

The TDR waveforms of 136 working nails (with known locations of couplers) installed in seven sites were examined. Among the 192 couplers installed at these nails, 129 (67%) did not show return of reflections at their corresponding locations. The remaining 63 (33%) couplers showed return of reflections of magnitude ranging from 6% to 35% of those reflections induced at the nail ends. The results are summarized in Table 2.1. It is noted that only 17 (less than 10%) out of 192 couplers returned with pulse reflections of magnitude more than 20% of that induced at the nail end. Figure 2.8 presents a typical example of waveform of the working nails examined. It shows that no significant reflection is returned at the locations of the couplers.

Table 2.1 Magnitude of Electrical Pulse Reflected from Couplers

No. of Sites	No. of Soil Nails	No. of Couplers	No. of Cases without Notable Pulse Reflection	No. of Cases with Notable Pulse Reflection (Magnitude in terms of % of that from the Nail End)			
				< 10%	10 - 20%	20 - 30%	30 - 35%
7	136	192	129	8	38	16	1
Total		192	129 (67%)	63 (33%)			

The above results indicate that the presence of couplers in soil nails would not significantly affect the interpretation of TDR test results.

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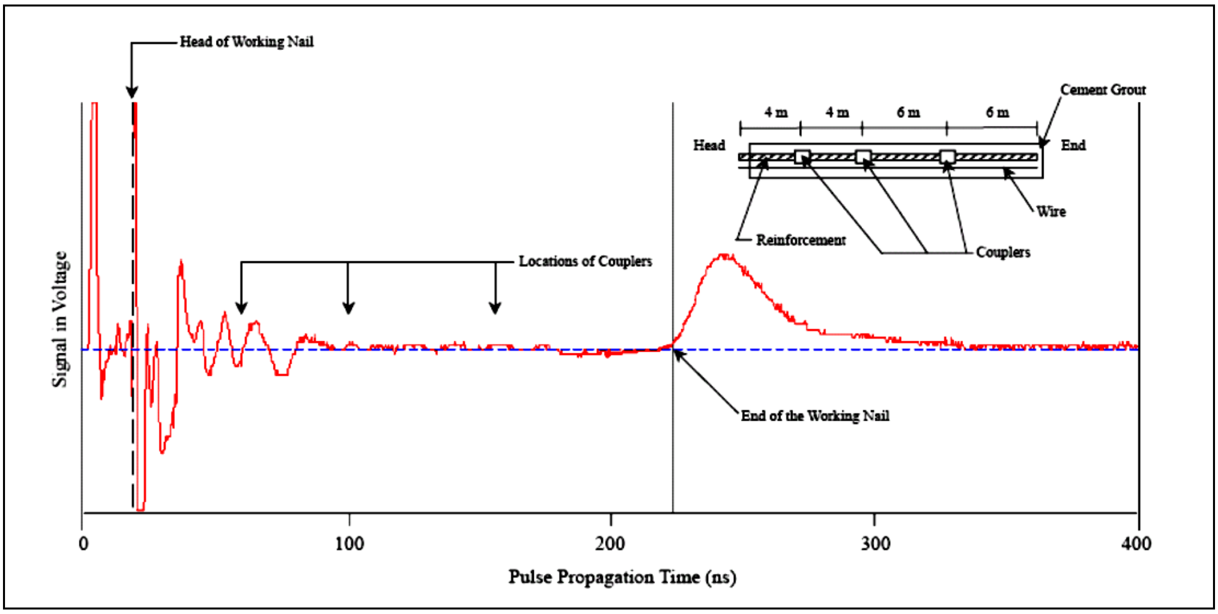

Figure 2.8 Typical Example of TDR waveform of a Working Nail with Couplers

3 TDR Tests on Pre-fabricated Soil Nails with Defects

3.1 Trial Arrangement

Soil nails with built-in grout defects were prefabricated for studying the effects of grout defects on the TDR pulse propagation velocity and waveform (Figure 3.1). There were a total of 19 prefabricated soil nails with lengths of either 6 m or 12 m. They were divided into four groups (A, B, C and N) in accordance with their configurations (see Figure 3.2). Detailed dimensions of the soil nails are given in Appendix A.

Apart from the two reference soil nails in Group N (which were fully grouted without voids for determination of the TDR pulse propagation velocity), all the nails in Groups A to C were constructed with different degree and pattern of voids in the grout sleeves (Table 3.1). The voids were placed at various locations along the lengths of the nails.

Table 3.1 Details of Configurations of Prefabricated Nails

Prefabricated Nail Group	Void Pattern	Nail Length	Void Fractions (Length of Void / Length of Soil Nail)
A (Soil Nail Nos. A1 - A7)	A void at one end of nail	6 m	0.25, 0.33 & 0.5
		12 m	0.17, 0.25, 0.33 & 0.5
B (Soil Nail Nos. B1 - B6)	An intermediate void	6 m & 12 m	0.25, 0.33 & 0.5
C (Soil Nail Nos. C1 - C6)	Two intermediate voids	6 m & 12 m	0.25, 0.33 & 0.5

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Figure 3.1 Prefabricated Soil Nails with Built-in Grout Defects

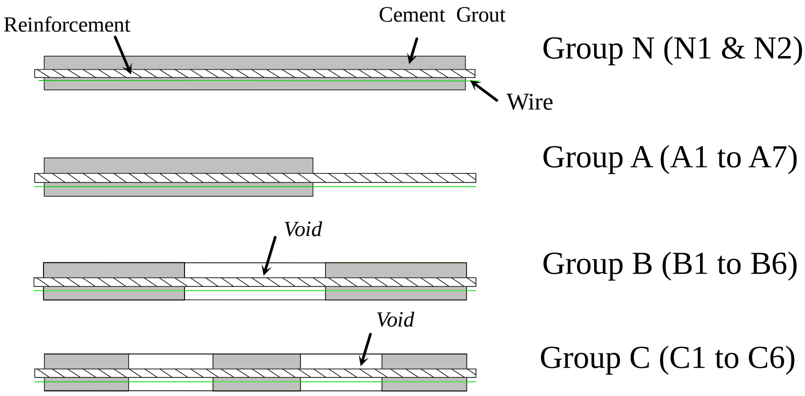

Figure 3.2 Configurations of the Prefabricated Soil Nails with Grout Defects (Grout Pipes Not Shown for Clarity)

TDR tests were carried out at both ends of the soil nails. Group A nails were used to study void at either nail head or nail end.

Each soil nail was constructed in a 150 mm diameter clear PVC pipe and installed with a single conducting wire and four different types of grout pipe, namely Types B, D, E and F. The grout pipes were produced by various manufacturers (namely : Take Luck for Type B, Conwy for Type D, and Shun Koon for Types E & F) with different wire sizes (i.e. 0.8 mm for Types B, D, & F, and 1.0 mm for Type E respectively). Twin conducting wires were installed in each grout pipe (Figure 3.3). All the prefabricated soil nails were installed with centralisers. For those soil nails of 12 m long, couplers were used to connect the steel bars. The typical cross section of the soil nails is shown in Figure 3.4.

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Figure 3.3   Grout Pipes with Embedded Copper Wires

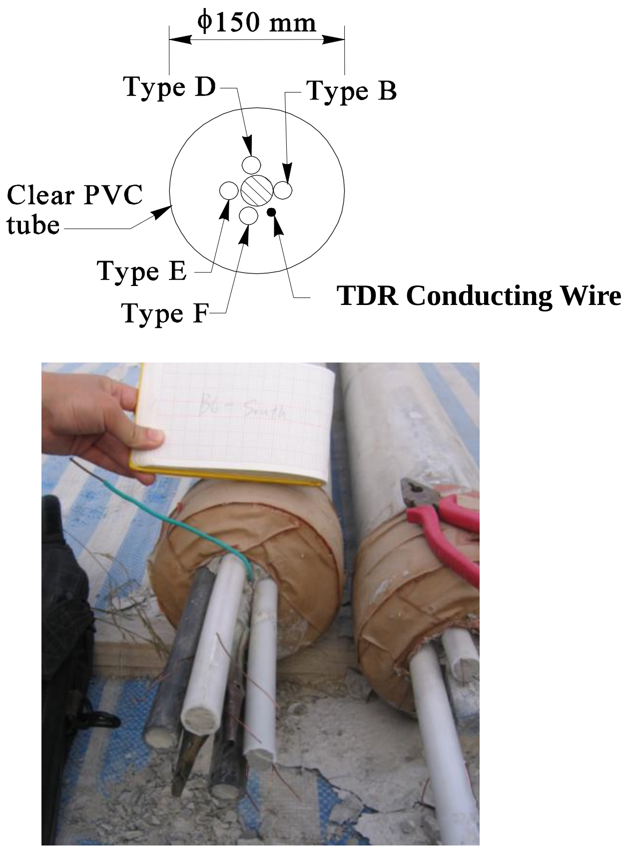

Figure 3.4   Typical Cross Section of the Prefabricated Soil Nails

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The TDR pulses propagation velocities in air were determined from the reference nails (nail nos. N1 and N2) before grouting. After grouting, TDR tests were conducted on the prefabricated soil nails using the single conducting wire and the four types of grout pipes embedded with twin conducting wires in turn. The reference TDR pulse propagation velocity for each type of conducting wire set was determined by averaging the respective results from the two reference nails. Since the TDR tests were conducted from both ends of the soil nails, there are a total of 38 sets of test results for analysis (i.e. 19 soil nails each with North (N) and South (S) ends).

3.2 Test Results

The TDR deduced lengths were checked against the current precision limit (i.e. 85% of designed nail length) of the testing method. According to GEO (2014), a soil nail with the TDR-deduced length less than 85% of the design length is considered as having an anomalous result. The TDR waveforms of nails with TDR deduced length below the current precision limit were further examined to check if any anomalous reflected pulses were generated in the waveforms. Selected waveforms are presented in Figures 3.5, 3.6 and 3.7 for soil nails of Groups A, B and C respectively. In these figures, both the inferred locations of void and nail end (i.e. computed by the pulse propagation velocities in air and in grout respectively) and the interpreted nail end (i.e. the position where the pulse with largest amplitude starts to rise) are annotated on the waveforms for comparison.

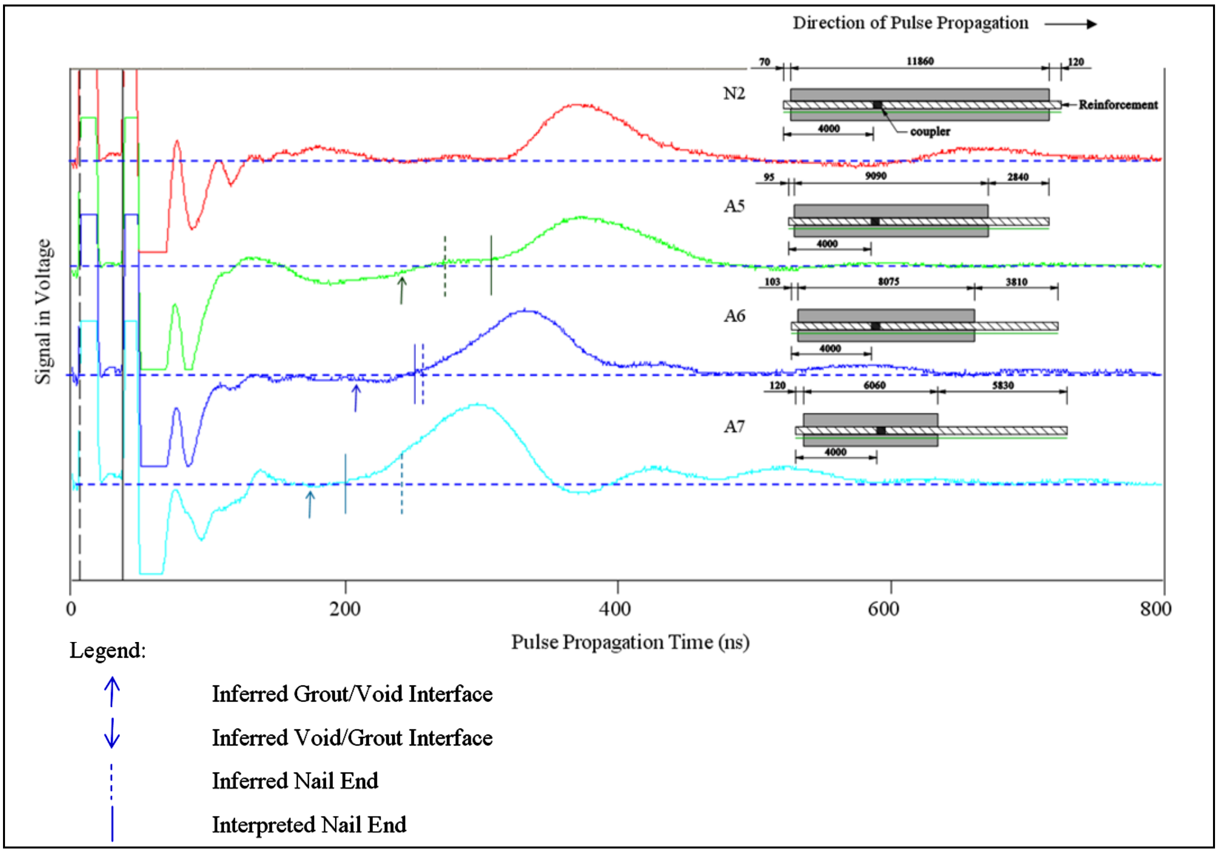

Figure 3.5 Comparison of TDR Waveforms (Single Conducting Wire) of Soil Nails A5, A6 and A7

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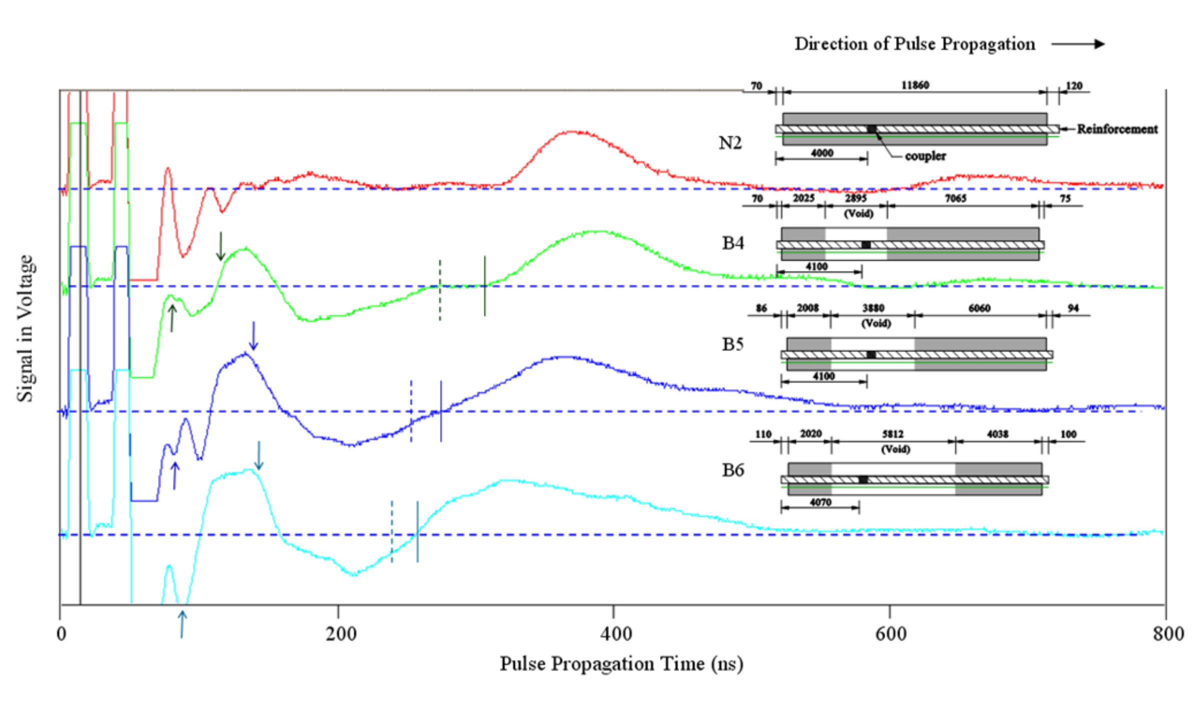
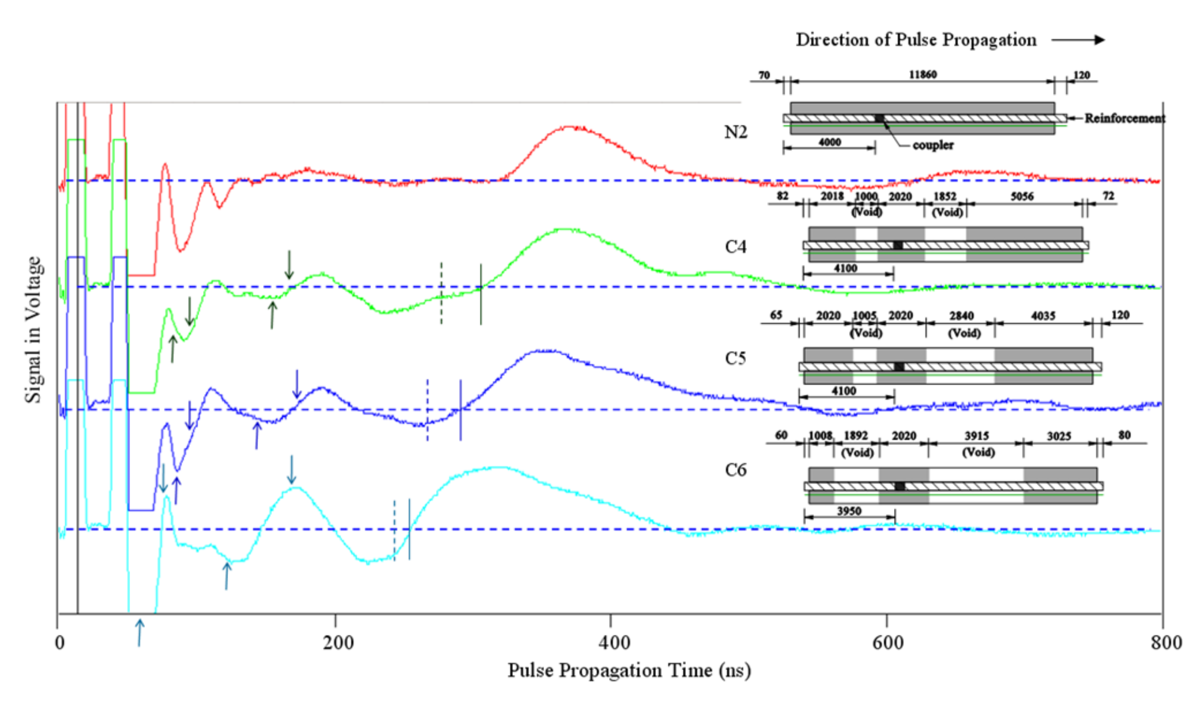


Note: See Figure 3.5 for legend.

Figure 3.6 Comparison of TDR Waveforms (Single Conducting Wire) of Soil Nails B5, B6 and B7



Note: See Figure 3.5 for legend.

Figure 3.7 Comparison of TDR Waveforms (Single Conducting Wire) of Soil Nails C5, C6 and C7

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3.3 Discussion of Test Results

3.3.1 General

As discussed in Section 2 above, the presence of grout defects in a soil nail would 'shorten' the deduced soil nail length and create additional pulse reflections in the waveform. To investigate the capability of TDR tests for identifying major grout defects, all 38 sets of TDR results in this study (i.e. the single conducting wire and the four types of grout pipes embedded with twin conducting wires) were examined.

3.3.2 Effect of Void on Deduced Nail Length

Based on the TDR deduced lengths of the test nails (Table 3.2), the performance of single conducting wire is found to be generally better than that of twin conducting wires embedded in grout pipes for identification of substantial voids. The overall performance mainly depends on the void fraction which is defined as void length/nail length. There are four void fractions in the test nails (0.17, 0.25, 0.33 and 0.5). The following observations can be made from Table 3.2:

(a) Using the current precision limit (i.e. 85% of designed nail length), the TDR tests were generally unable to pick out the soil nails with void fractions of 0.17 and 0.25 (i.e. the TDR deduced length still falls within the current precision limit), except for a few isolated cases.

(b) For those test nails with void fraction of 0.33, the TDR tests using single conducting wire rejected all the tested nails in Group A, but they failed to distinguish half of the tested nails in Groups B and C. TDR tests using a single conducting wire still ranked highest with an overall success rate of 67%. TDR tests using grout pipes with embedded wires still failed to reject most of the tested nails, except Type D grout pipe (which is able to distinguish all the tested nails in Group A). The success rate of Type D grout pipe wire sets (for picking out grout defects) is about 30%, and the performance of this wire set appears to be better than the other types of wire sets.

(c) TDR tests by means of the single conducting wire successfully picked out all 12 tested nails with void fraction of 0.5 as defective nails (i.e. 100% success rate). However, the success rate of the TDR tests using grout pipes with embedded wires ranged between 33% and 55% only.

The success rates of applying TDR test results for rejecting defective soil nails in terms of void configuration (i.e. nail group) are summarized in Table 3.3. The performance of TDR tests using a single conducting wire was consistently better than those using grout pipes with embedded conducting wires.

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Table 3.2 Success Rate (%) in Rejecting Prefabricated Soil Nails with Controlled Grout Defects (in Terms of Void Fraction)

Void Fraction (No. of Soil Nails Tested)	Twin Conducting Wires Embedded in Grout Pipe				Single Conducting Wire
	Type B	Type D	Type E	Type F	
0.17 (2)	0%	100%	0%	0%	0%
0.25 (12)	0%	17%	0%	0%	8% (1)
0.33 (12)	0%	33%	17%	0%	67% (8)
0.50 (12)	33%	50%	50%	50%	100% (12)
Overall (38)	11%	37%	21%	16%	55%

Table 3.3 Success Rate (%) in Rejecting Prefabricated Soil Nails with Controlled Grout Defects (in Terms of Void Configuration)

Tested Nail Group (Total Nos.)	Twin Conducting Wires Embedded in Grout Pipe				Single Conducting Wire
	Type B	Type D	Type E	Type F	
A (14)	21%	79%	43%	21%	64%
B (12)	8%	8%	0%	8%	58%
C (12)	0%	17%	17%	17%	42%
Overall (38)	11%	37%	21%	16%	55%

The main reason for better performance in the case of single conducting wires is that the critical void fraction for a single conducting wire (i.e. the void fraction in a soil nail that theoretically makes the deduced nail length equals to 85% of designed nail length, see Appendix B for the mathematical derivation) is much lower than those for the other wire sets, as the contrast of pulse propagation velocity in air and that in grout of the single wire is more distinct than grout pipes with embedded wires. It means that by using grout pipe with embedded wires, larger void fractions in the nail are required to make the TDR deduced length less than the precision limit, as compared with the single conducting wire. The ratio of calibrated pulse propagation velocities of the reinforcement-wire configuration encased in grout to that in air for single conducting wires (0.42) is smaller (except for the case of Type D grout pipe with similar ratio). It makes the theoretical critical void fractions for both the single conducting wires (0.26) and the grout pipe Type D (0.25) substantially smaller than the other types of embedded wires (ranging from 0.32 to 0.36, see Table 3.4). Since the minimum critical void ratio marginally exceeds 0.25, it is not surprising that TDR test is unable to reject most of the tested nails with void fractions of only 0.17 or 0.25.

Although the performance of TDR test using Type D grout pipe with embedded conducting wires is found comparable to that of using single conducting wire in Group A soil nails, the propagation time could differ by about 24% to 39% of the reference nails N1 and N2. This casts some doubts on the reliability of its calibrated reference propagation velocity and correspondingly the deduced nail lengths. As such, its performance in some of the tested nails is questionable. The differences could arise from the presence of multiple reflections that were superimposed and taken as the major reflection from the nail end.

Table 3.4 Theoretical Critical Void Fractions of Prefabricated Soil Nails

	Twin Conducting Wires Embedded in Grout Pipe				Single Conducting Wire
	Type B	Type D	Type E	Type F	
Calibrated Pulse Propagation Velocity in Grout, *Vg* (m/ns)	0.1161	0.0866	0.1041	0.1093	0.0843
Calibrated Pulse Propagation Velocity in Air, *Va* (m/ns)	0.1995	0.2132	0.2068	0.2013	0.1994
Ratio of Velocity (*Vg*/*Va*)	0.58	0.41	0.5	0.54	0.42
Void Fraction	0.36	0.25	0.32	0.33	0.26

3.3.3 Effect of Void on TDR Waveform

The waveforms of the soil nails with TDR deduced length less than 85% of designed nail length have been studied to identify any anomalies.

A careful examination of the waveforms showed that ‘anomalies’ in the forms similar to those in Figures 2.3 to 2.5 were induced before the major reflection from the nail end (see examples in Figures 3.5 to 3.7). The amplitude of these ‘anomalies’ is generally over 50% of that of the major reflection at the nail end. These support the argument that the presence of ‘anomalies’ with comparable amplitude may indicate the presence of sizeable voids along the grout annulus of a soil nail.

Though the ‘anomalies’ in the waveforms can provide some clues to the potential presence of grout defects, in many cases the position and extent of the voids could not be accurately located due to superimposition and cancelling out of reflections. The inferred positions of the grout interface and nail end (based on theoretical calculation) do not match well with the starting points of the reflected pulses as observed in the waveforms in most situations.

A probable reason for the above mismatch is the interference of the reflected pulses in the TDR waveform. The measured total propagation time of the tested nails (with lengths of

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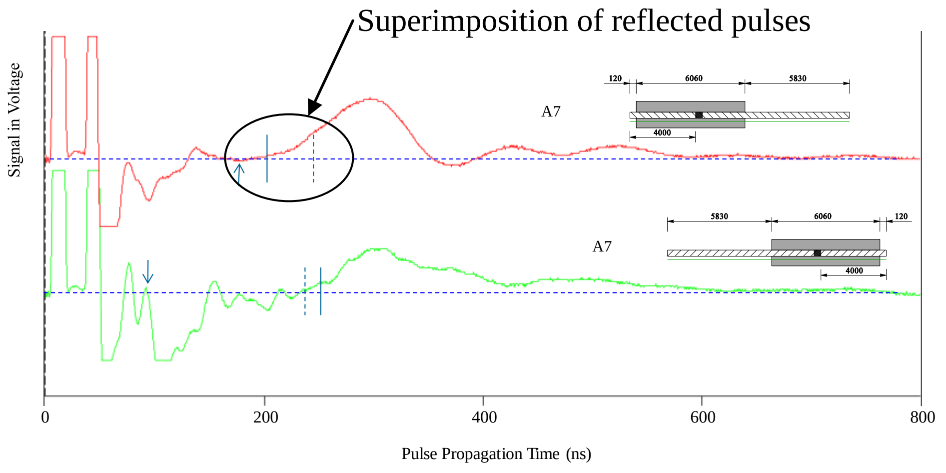
6 m and 12 m) ranges from about 100 ns to 300 ns. However, the typical time period of the reflected pulses are in the order of several tens or even over hundred nanoseconds, which is far wider than that of the input transmitted pulse (i.e. 2 ns or 10 ns). Worse still, the required time for the TDR pulse passing through the void is relatively short, say, taking only about 10 ns to pass through a 2 m long void, which makes the reflected pulses generated at the grout to void interface and that at the void to grout interface of the same void section significantly interfere with each other.

It is considered that the problem of interference of pulses is less serious for longer nails, as the total propagation time is comparatively longer. Further investigation of this postulation may be warranted.

3.3.4 Effect of Void Position on Deduced Nail Length

For the Group A soil nails (nail nos. A1 to A7), each nail had a void at one end (north end) of the nail. The TDR tests were conducted at both the north end (N) and south end (S) of the nails. The TDR deduced lengths of the soil nail nos. A1N to A7N (tested with a void at the nail end) were consistently shorter than those tested with a void at the nail head (i.e. A1S to A7S). Such an observation is not apparent for the other two Groups (B and C) with intermediate grout defects.

It is conjectured that the reflected pulses from the void interface are superimposed with the major reflection from the nail end for the cases of A1N to A7N, which result in shorter interpreted travel time of the pulse (Figure 3.8). Presence of void at nail end therefore more frequently falls outside the precision limit of the testing method.



Note: See Figure 3.5 for legend.

Figure 3.8 Comparison of TDR Waveforms (Single Conducting Wire) of Soil Nail A7

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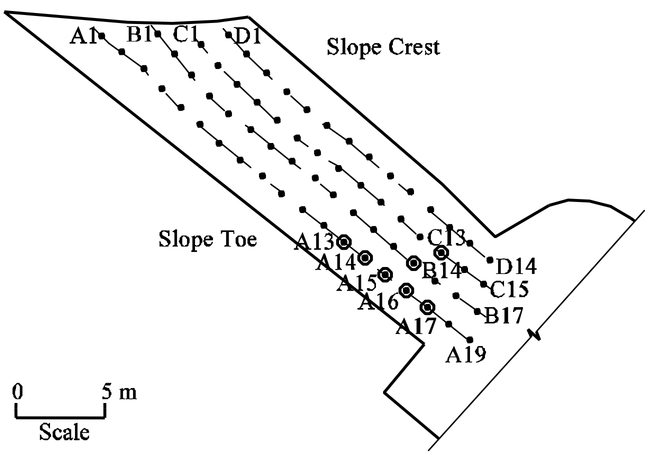
As discussed in Sections 2 and 3 above, anomalous TDR waveforms need to be carefully interpreted in order to differentiate such overlapping of multiple reflected pulses (i.e. waveform comprising multiple peaks) due to the presence of voids in the grout sleeves Based on the findings of the study, procedures for identification of soil nails with possible significant defects in the cement grout sleeve are suggested in Appendix C.

4 Case Study

A 10 m high and 115 m long soil cut slope standing at an angle of 50^{o} was upgraded by installing soil nails. The works comprised installation of 95 soil nails, amongst which 65 numbers were installed at the northern portion and 30 numbers at the southern portion of the slope. All the soil nails were 7 m long and without couplers.

During an independent site audit, the TDR-deduced lengths of five out of ten nails tested were found to be less than 85% of the designed nail length, and some anomalous TDR waveforms were observed. Further TDR testing of the remaining nails at the slope revealed that two more nails had short TDR-deduced lengths and anomalous TDR waveforms. The seven nails with anomalous TDR test results, namely soil nail No. A13 to A17, B14 and C13 are located in a cluster at the northern portion of the slope (see Figure 4.1).



Legend:

- ● Soil nails with normal TDR test results
- ⦿ Soil nails with anomalous TDR test results

Figure 4.1 Layout of Soil Nails at the Northern Portion of the Slope

The TDR waveforms of these seven nails depicted the following features (e.g. Figure 4.2(b)):

(a) significant local reflections between the major reflections from the nail head and that from the nail end, and

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(b) shorter pulse propagation time to the end of the nails.

The TDR waveforms of these seven nails bear some resemblance of the characteristics of the grout defects described in Section 2, suggesting anomalies possibly associated with the presence of voids in the grout sleeves. A review of construction records found that there were incidents of significant grout take at the northern portion of the slope during the grouting of these nails.

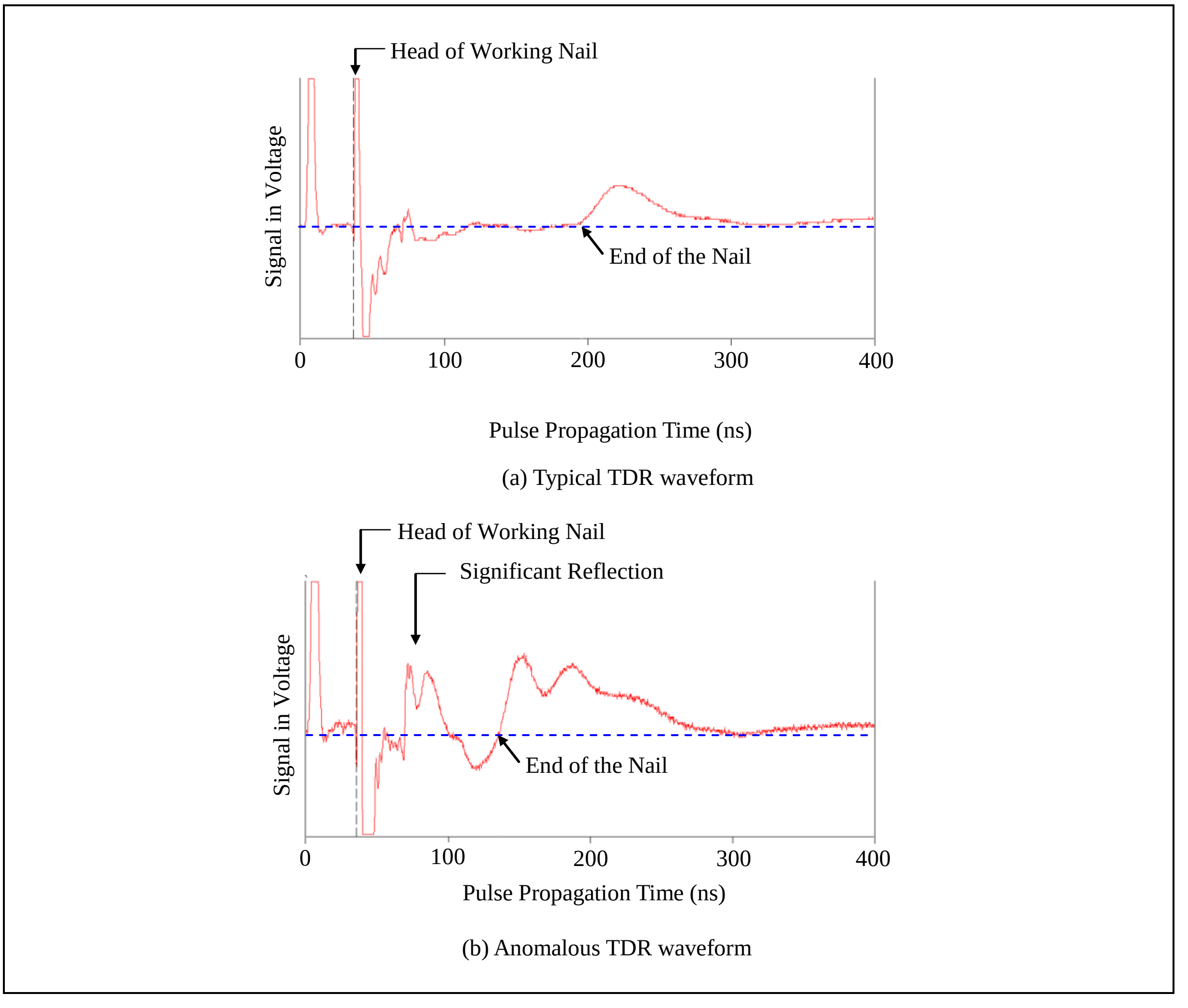

Figure 4.2 Typical and Anomalous TDR Waveforms Recorded

In order to supplement the TDR tests, another non-destructive testing (NDT) technique, Electrical Resistance Method (ERM), was carried out. This method is one of the NDT methods reviewed by Cheung & Lo (2005). According to theories, a soil nail measured with a high electrical resistance is likely to be associated with significant grout defects.

Figure 4.3 shows that the nails with high electrical resistance determined using ERM match with those with anomalous TDR results. This indicates that the anomalies were likely related to the existence of substantial voids in the seven nails. Most of the ERM and TDR

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results were in agreement, except for A17 in which ERM did not identify any anomaly.

Based on their TDR deduced lengths, the sizes of voids in the anomalous nails were likely to be over 2 m (i.e. with void fraction over 0.3). Given the sizes of the void were likely to be substantial, it was decided to remove the concrete nail heads for inspection by inserting a CCTV camera into the underneath voided sections. The recorded images confirmed that there were sizeable voided sections in these nails. The seven nails were subsequently replaced by new soil nails and TDR was conducted again to check the grout integrity of replacement nails, both during grouting operation and after installation. No anomalous test results were observed from the testing of these replacement nails.

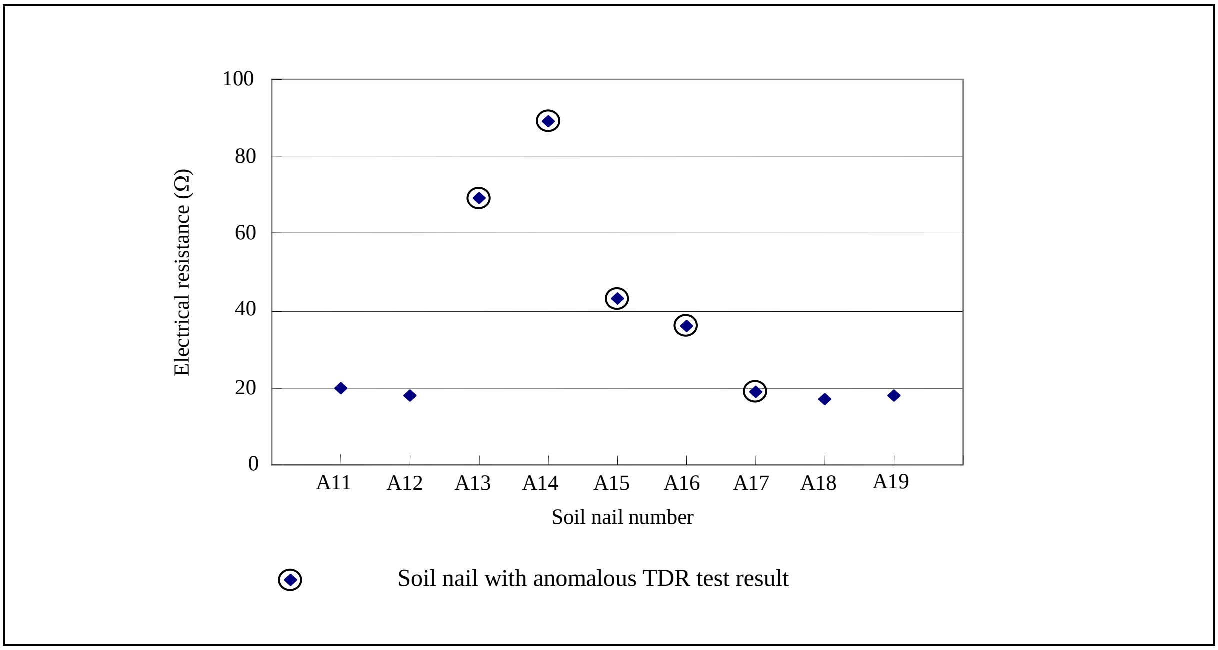

Figure 4.3 Variation of Electrical Resistance along Row A Nails Using ERM

The details of this case study and another case study involving the use of TDR tests and two other NDT techniques (including ERM and Vector Magnetometry Survey) to infer grout defects in nails were reported by Pun et al (2008).

5 Conclusions

The following conclusions are made from the present study.

(a) The presence of voids in soil nails would bring about a reduction in the deduced nail length. Subject to the current precision limit (i.e. 85% of designed nail length), TDR test using the conventional single conducting wire is capable of distinguishing soil nails with significant grout defects (e.g. void fraction larger than about 0.3 of the total soil nail length).

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(b) TDR test using the conventional single conducting wire is found feasible for identifying significant defects in the cement grout sleeve of a soil nail.

(c) The performance of TDR test using conducting wires embedded in a grout pipe is considered generally unsatisfactory due to the small contrast in pulse propagation velocities in air and grout, and the occurrence of multiple reflections. Therefore, the use of grout pipes with embedded wires is not recommended for identification of grout defects.

(d) Additional reflected pulses in the TDR waveform with an amplitude over 50% of that of the major reflection from nail end may indicate the presence of substantial voids in the grout annulus.

(e) If the reflections arising from a void in cement grout are interfered by the reflection arising at the end of the reinforcement-wire pair, the corresponding travel time may be shifted, which may affect the determination of the nail end.

6 References

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Appendix A

Configurations of the Prefabricated Soil Nails with Grout Defects

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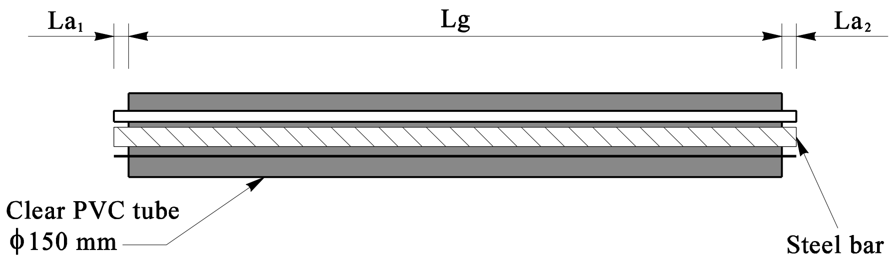
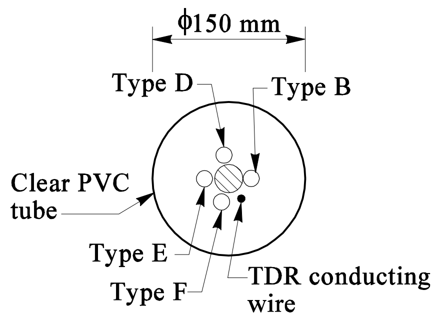
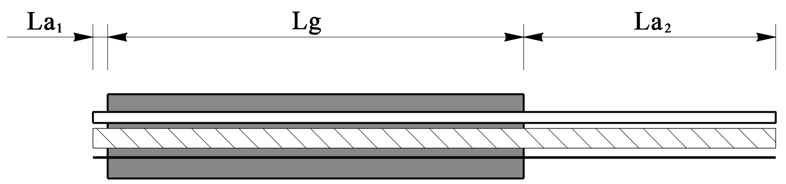


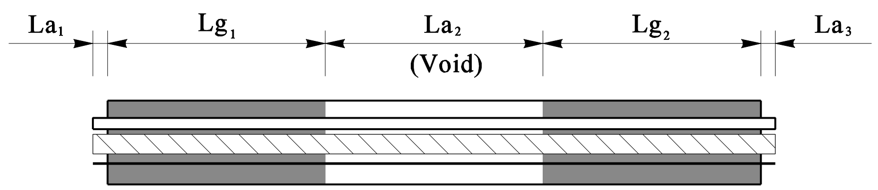
Soil Nail N1-N2



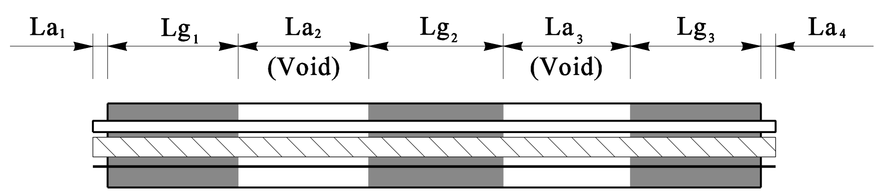
Typical Section



Soil Nail A1-A7



Soil Nail B1-B6



Soil Nail C1-C6

	La_1	Lg	La_2	Total
N1	0.05	5.9	0.05	6
N2	0.05	11.9	0.05	12

	La_1	Lg	La_2	Total
A1	0.05	4.5	1.45	6
A2	0.05	4	1.95	6
A3	0.05	3	2.95	6
A4	0.05	10	1.95	12
A5	0.05	9	2.95	12
A6	0.05	8	3.95	12
A7	0.05	6	5.95	12

	La_1	Lg_1	La_2	Lg_2	La_3	Total
B1	0.05	1	1.4	3.5	0.05	6
B2	0.05	1	1.9	3	0.05	6
B3	0.05	1	2.9	2	0.05	6
B4	0.05	2	2.9	7	0.05	12
B5	0.05	2	3.9	6	0.05	12
B6	0.05	2	5.9	4	0.05	12

	La_1	Lg_1	La_2	Lg_2	La_3	Lg_3	La_4	Total
C1	0.05	1	0.5	1	0.9	2.5	0.05	6
C2	0.05	1	0.5	1	1.4	2	0.05	6
C3	0.05	0.5	0.5	1	2.4	1.5	0.05	6
C4	0.05	2	1	2	1.9	5	0.05	12
C5	0.05	2	1	2	2.9	4	0.05	12
C6	0.05	1	2	2	3.9	3	0.05	12

Notes :

(1) Each nail shall installed with 3 grout pipe (Types B, D, E & F) and 1 conventional TDR wire
(2) Both the PVC pipe and the grout pipes shall be fully grouted
(3) Both ends of the nails shall be accessible for TDR testing

Legend:

- Conventional TDR wire
- Grout pipe with copper wires embedded (Types B, D, E & F)
- ϕ25 mm steel bar
- Grout

Note: All dimensions are in meters.

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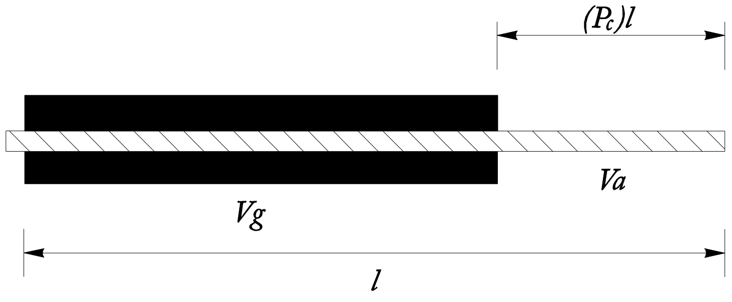
Appendix B

Calculations of Theoretical Critical Void Fraction



$$\text{Measured Propagation Time} = \frac{(1\text{-}P_c)l}{V_g} + \frac{P_c l}{V_a} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \quad \text{(B.1)}$$

Where P_c = theoretical critical void fraction
l = as-built nail length (m)
V_g = calibrated pulse propagation velocity in grout (m/ns)
V_a = calibrated pulse propagation velocity in air (m/ns)

For deduced length = 0.85l

$$\text{Measured Propagation Time} = \frac{0.85l}{V_g} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(B.2)}$$

By substituting (B.1) into (B.2),

$$\frac{(1\text{-}P_c)l}{V_g} + \frac{P_c l}{V_a} = \frac{0.85l}{V_g}$$

$$(1\text{-}P_c) + P_c\left(\frac{V_g}{V_a}\right) = 0.85$$

$$P_c = \frac{0.15}{\left(1\text{-}\frac{V_g}{V_a}\right)}$$

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Appendix C

Suggested Procedures for Identification of Soil Nails with Possible Significant Defects in the Cement Grout Sleeve

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Suggested Procedures for Identification of Soil Nails with Possible Significant Defects in the Cement Grout Sleeve

1. General

1.1 Based on a study conducted by the GEO (refers to Sections 2 & 3 this report), the following procedures for interpretation of anomalous test results possibly associated with significant defects in the cement grout sleeve of soil nails are suggested.

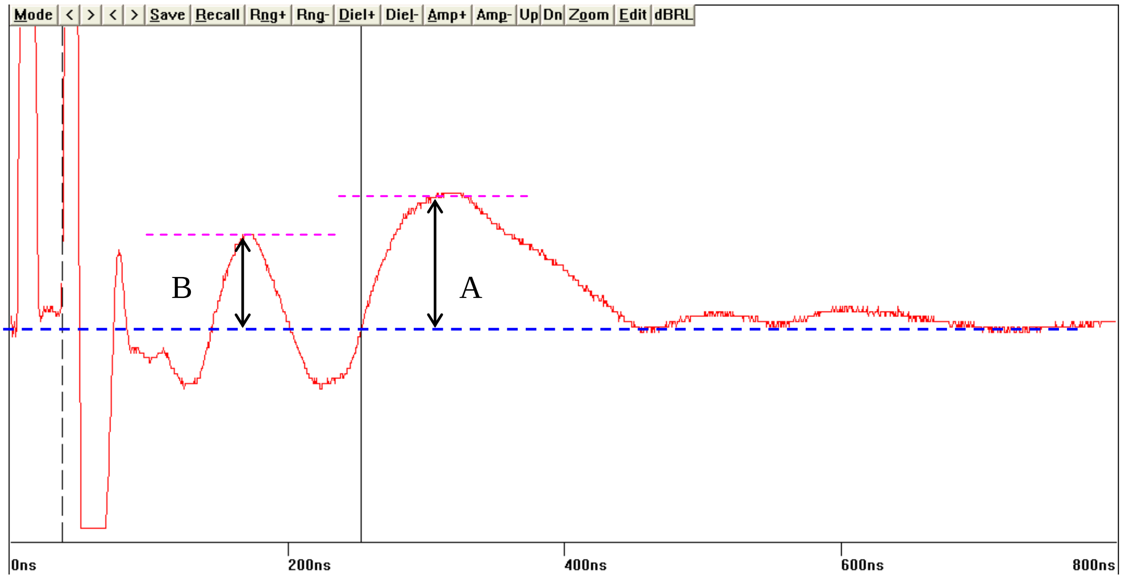
2. Interpretation of Abnormal Test Results

2.1 <u>TDR Waveform with Significant Reflection Preceding the Major One</u>

2.1.1 Determine the nail length based on the travel time of the major reflection.

2.1.2 Examine the waveform for any significant reflection preceding the major one with amplitude exceeding 50% of the major reflection (i.e. B > 0.5A).

2.1.3 If the TDR deduced length determined from Section 2.1.1 is less than 85% of the design length and there is significant reflection preceding the major one, it is likely that significant defects exist in the cement grout sleeve.



2.2 <u>TDR Waveform with Major Reflection Comprising Multiple Peaks</u>

2.2.1 For soil nails with major reflection comprising multiple peaks, determine the time of travel as follows: -

(a) Identify the major reflection as the one with the largest amplitude (A).

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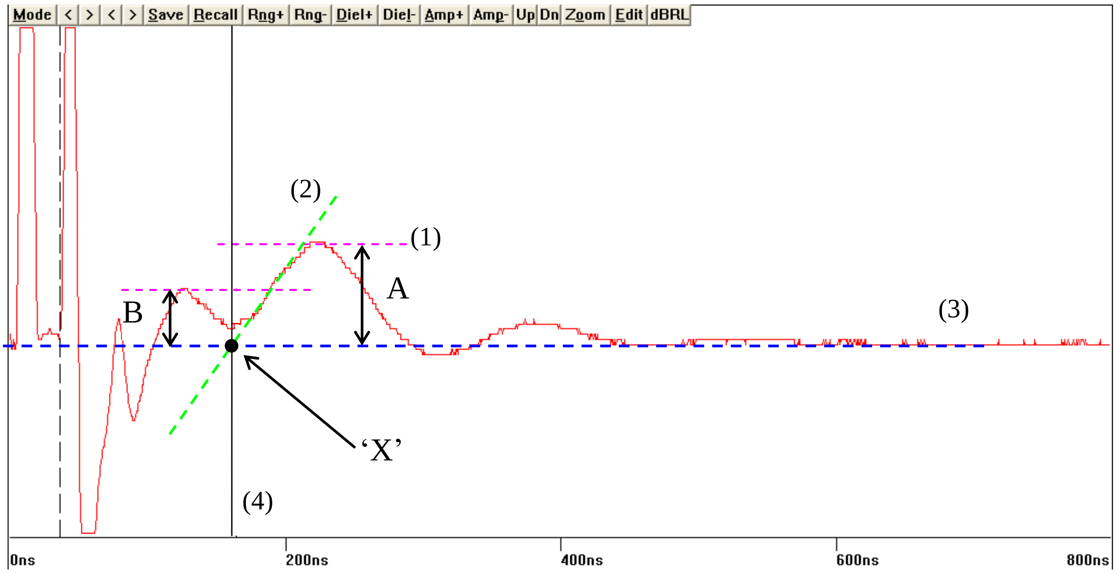
(b) Extend the left sloping side of the major reflection.

(c) Extend the levelled tail part of the waveform.

(d) Take the time of travel as the interception point of the lines formed in steps (b) and (c) respectively, i.e. point 'X'.



2.2.2 Determine the nail length based on the time of travel determined in 2.2.1.

2.2.3 If the TDR length determined is less than 85% of the design length, the tested soil nail may be considered as having an anomalous result.

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斜坡岩土工程手冊(1998)，308頁(1984年英文版的中文譯本)。

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Geoguide 3	Guide to Rock and Soil Descriptions (1988), 186 p. (Reprinted, 2000).
Geoguide 4	Guide to Cavern Engineering (1992), 148 p. (Reprinted, 1998).
Geoguide 5	Guide to Slope Maintenance, 3rd Edition (2003), 132 p. (English Version).
岩土指南第五冊	斜坡維修指南，第三版(2003)，120頁(中文版)。
Geoguide 6	Guide to Reinforced Fill Structure and Slope Design (2002), 236 p.
Geoguide 7	Guide to Soil Nail Design and Construction (2008), 97 p.

GEOSPECS

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