USE OF TIME DOMAIN REFLECTOMETRY TO DETERMINE THE LENGTH OF STEEL SOIL NAILS WITH GROUT PIPE WITH EMBEDDED COPPER WIRES

GEO REPORT No. 228

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CIVIL ENGINEERING AND DEVELOPMENT DEPARTMENT

THE GOVERNMENT OF THE HONG KONG

SPECIAL ADMINISTRATIVE REGION

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This report is largely based on GEO Technical Note No. TN 2/2007 produced in August 2007

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First published, July 2008

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PREFACE

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R.K.S. Chan
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July 2008

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FOREWORD

This report presents the findings of a feasibility study of using a new type of grout pipe for grouting and TDR test. The new type of grout pipe with embedded copper wires simplifies the current procedure of installing a copper wire for TDR test. The uncertainty of the TDR test associated with the new setting has been studied by a precision experiment on field using prefabricated soil nails and working soil nails.

This study was conducted by Dr W.M. Cheung, Mr. K.W. Shum and Ms. P.F.K. Cheng of the Standards and Testing Division. The overall supervision is carried out by Dr D.O.K. Lo and Dr W.M. Cheung. Much of the data collection and analyses were performed by the technical staff, Mr. M. Ng, Mr. K.Y. Wong and Mr. P.C. Cheung. Valuable assistance was given by Halcrow China Ltd in preparing the prefabricated soil nails and arranging the field tests. All contributions are gratefully acknowledged.

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ABSTRACT

Time domain reflectometry (TDR) has been identified as a potential non-destructive method for determining the length of installed steel soil nails with pre-installed wires. This report presents the findings of a feasibility study of using a new type of grout pipe with embedded copper wires for grouting and TDR test. By integrating the copper wire and the grout pipe, the procedure of pre-installing a wire alongside the steel bar can be streamlined.

The performance of the newly developed grout pipe with embedded copper wires for TDR test has been studied and benchmarked with that of the conventional wire. The benchmarking includes a precision experiment using prefabricated soil nails and working soil nails at 11 LPM sites. The overall uncertainty of TDR tests using the grout pipe with embedded copper wires is found to be smaller than that of using conventional wire. However, the new grout pipe seems to have a slightly higher material defect rate than that of the conventional wire. In all, the use of grout pipe with embedded copper wires is found to be feasible for both the grouting works and TDR test.

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CONTENTS

1. INTRODUCTION

Time domain reflectometry (TDR) has been identified as a potential non-destructive method for determining the length of installed steel soil nails with pre-installed wires. Various sources of uncertainty associated with the test have been examined (Cheung, 2006). In the current practice, among other accessories such as grout pipe and centralisers, a copper wire insulated with plastic sheath (referred to as conventional wire thereafter) has to be fixed alongside the steel bar before the soil-nail reinforcement is inserted into a drillhole. In order to simplify the procedure of installation, a new type of grout pipe with embedded copper wires has been developed. The new grout pipe can be used for both grouting a drillhole and facilitating TDR test.

This report presents the findings of a feasibility study of using the new type of grout pipe for grouting and TDR test. The uncertainty of the TDR test associated with the new setting will be presented. The guidelines on testing procedure and interpretation of test results will also be given.

2. GROUT PIPE WITH EMBEDDED COPPER WIRES

Similar to that for the conventional wire, a grout pipe used for drillhole grouting is commonly fixed alongside the soil-nail reinforcement. By integrating the copper wire and the grout pipe, the procedure of pre-installing a conventional wire alongside the steel bar can be streamlined. A pair of copper wires are encapsulated diametrically along the grout pipe (Plate 1). The copper wires are completely sheathed within the wall of the grout pipe to form an insulated cover. Two types of new grout pipes, referred as Type 1 and Type 2 pipes, were examined. They are supplied by different local manufacturers.

3. TESTING PROCEDURE AND INTERPRETATION OF TDR TEST RESULTS

The guidelines on testing procedure and interpretation of TDR test results are given in Appendix A. They are essentially the same as those adopted for TDR test with conventional wire. The test basically comprises two parts, viz. calibration of pulse propagation velocity from soil nails of known length and measurement of the time for a pulse to propagate from the soil-nail reinforcement head to its end. The purpose of calibration is to determine the reference pulse propagation velocity which can be used to deduce the length of test soil nails at the same site of the same grout mix and same type of grout pipe with embedded copper wires. In general, at least three soil nails of known lengths should be selected for calibration. These soil nails can be of any bar diameter. They should preferably be the longest soil nails among the test soil nails because for a given test instrument, the resolution on the interpreted travel time of a pulse along a long soil nail is comparatively higher than that for a short one.

4. UNCERTAINTY OF SOIL-NAIL LENGTH ESTIMATION BY TDR TEST USING GROUT PIPE WITH EMBEDDED COPPER WIRES

4.1 General

In a TDR test, the interpreted time for a pulse to travel from the soil-nail reinforcement

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head to its end, t, and the reference pulse propagation velocity, v_r, calibrated from soil nails of known lengths are the two key parameters that have to be known for the estimation of soil-nail length, and factors affecting these two parameters will introduce uncertainty to the estimated soil-nail length. Various sources of uncertainty of a TDR test using conventional wire have been studied (Cheung, 2006). These uncertainties can be classified as nail-unrelated and nail-related sources.

Nail-unrelated uncertainties comprise human judgement in the carrying out of the test and interpretation of results, and built-in error of the testing instrument. Nail-related uncertainties consist of those arising from the natural variability in the soil-nail characteristics. They include the variability of the grout pipe, integrity of grout sleeve, reinforcement size (length and diameter), as well as other unaccounted factors. According to Cheung (2006), by adopting a standard procedure for testing and interpretation of test results, the overall uncertainty can be minimised. The remaining major sources of nail-unrelated and nail-related uncertainties become those associated with human judgement and the integrity of grout sleeve respectively.

4.2 Human Judgement

The variation of human judgement in defining the point of reflection from the soil-nail end in a TDR waveform is the major factor that affects the interpreted travel time of a pulse in practice. The reason is that the so-called step pulse generated by a TDR cable fault detector is indeed a smooth rising signal. Consequently the reflection from a soil-nail end is not a sharp step but rather a smooth rising signal, and sometimes this may obscure the identification of the point of initial arrival of the reflected signal. The variation of human judgement in defining the point of reflection can be further divided into two categories, namely single-operator and multi-operator uncertainties.

The single-operator uncertainty arises from the natural variability of a person in carrying out a test or measurement, even though the tests or measurements are performed on identical test items using the same equipment and method. The multi-operator uncertainty is due to the variation between people in performing a test or measurement on identical test items using the same method. These uncertainties can be determined through a standard precision experiment in accordance with BS ISO 5725-2:1994 (BSI, 1994a).

4.2.1 Precision Experiment

The precision of a test method is defined as the closeness of agreement between independent test results obtained under stipulated conditions (BSI, 1994b). The conditions where test results are obtained with the same method on identical test items by the same operator using the same equipment are called ‘repeatability conditions’. In contrast, the conditions where test results are obtained with the same method on identical test items by different operators using different equipment are called ‘reproducibility conditions’. Precision depends only on the distribution of random errors and does not relate to the true value of the test item. In the context of soil nails, the precision of a TDR test is independent of the actual soil-nail length. The measurement of precision is usually expressed in terms of imprecision and computed as a standard deviation or a coefficient of variation (i.e. standard

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deviation/mean) of the test results. Low precision is reflected by a larger standard deviation or coefficient of variation.

In accordance with BS ISO 5725-1:1994 (BSI, 1994b), the single-operator uncertainty is termed as the 'repeatability standard deviation', which is the standard deviation of the test results obtained under 'repeatability conditions'. The multi-operator uncertainty is termed as the 'reproducibility standard deviation', which is the standard deviation of the test results obtained under 'reproducibility conditions'. By carrying out a precision experiment and computing the standard deviations of the test results for single-operator and multi-operator, the uncertainties of human judgement can be estimated.

In this study, 18 operators performed TDR tests and identified the reflection from the soil-nail end following the same testing procedure. Three prefabricated soil nails (Nos. 1, 2 and 3) with lengths of 6 m, 12 m and 20 m respectively were used. Each soil nail was assembled with a conventional wire and the two types of grout pipes with embedded copper wires (Type 1 and Type 2). The pair of copper wires inside Type 1 grout pipe are named Wire A and Wire B and those in Type 2 grout pipe are named Wire C and Wire D. The conventional wire is named Wire E. Each operator took 5 rounds of measurements on each of the wires in a soil nail (i.e. 25 measurements on a soil nail). For each round of measurement, the interpreted pulse travel time of a grout pipe is taken as the average pulse travel time obtained from the two embedded copper wires.

The test results in terms of interpreted pulse travel time are summarised in Tables 1, 2 and 3. The method for calculating the statistics such as the general mean, variances and 95% confidence level ranges are given in BS ISO 5725-2:1994 (BSI, 1994a). The measurements on pulse travel time within one operator and between different operators have been checked for outlier using Grubb's Test (BSI, 1994a). During the tests, no signal was received from Wire C in prefabricated soil nails No. 1 and No. 3. It is suspected that the copper wires had been damaged during the grouting work. The performance of the grout pipes on site will be further discussed in Section 4.3.1.

4.2.2 Single-operator Uncertainty

The single-operator uncertainty in terms of coefficient of variation, *c.o.v.*, for Type 1 grout pipe is found to be 1.0% for soil nail No. 1, 0.5% for soil nail No. 2, and 0.3% for soil nail No. 3. That for Type 2 grout tube is found to be 0.5% for soil nail No. 2 (no signal received from soil nail Nos. 1 and 3). For the conventional wire, the subject *c.o.v.* is found to be 1.8% for soil nail No. 1, and 1.1% for soil nail Nos. 2 and 3. The results are summarised in Table 4.

Strictly speaking, the determined single-operator uncertainty has included the built-in error of the testing instrument. Given that the built-in error of a testing instrument is usually small, the said uncertainty has been assumed to be the single-operator uncertainty.

4.2.3 Multi-operator Uncertainty

The multi-operator uncertainty in terms of *c.o.v.* for Type 1 grout pipe is found to be

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1.6% for soil nail No. 1, 0.8% for soil nail No. 2, and 0.5% for soil nail No. 3. That for Type 2 grout tube is found to be 1.1% for soil nail No. 2 (no signal received from soil nail Nos. 1 and 3). For the conventional wire, the subject *c.o.v.* is found to be 4.2% for soil nail No. 1, 1.8% for soil nail No. 2, and 1.9% for soil nail No. 3. The results are summarised in Table 4. Similar to that of single-operator uncertainty, the contribution of the built-in error of the testing instrument in the said values of multi-operator uncertainty has been neglected.

4.2.4 Effect of Nail-unrelated Uncertainty on TDR-deduced Soil-nail Length

The nail-unrelated uncertainty (operator and built-in equipment uncertainties) of a TDR-deduced soil-nail length is introduced through the processes of calibration and testing. The effect of this uncertainty on the TDR-deduced soil-nail length can be determined using first-order-second-moment (FOSM) method (Harr, 1987). If the nail-unrelated uncertainty for Type 1 grout pipe, Type 2 grout pipe and conventional wire are assumed to be 1.6%, 1.1% and 4.2% respectively (i.e. the maximum values from multi-operator uncertainty), the corresponding *c.o.v.* on the deduced length are estimated to be 2.3%, 1.6% and 5.9% respectively. Details of FOSM method and the calculations are given in Appendix B.

4.3 Overall Uncertainty

4.3.1 General

As mentioned in Section 4.1, the overall uncertainty of a TDR test comprises nail-unrelated and nail-related components. Among different sources of uncertainty, some of them can be totally eliminated (e.g. using the same type of grout type/wire in the calibration and test soil nails), while others can only be minimised (e.g. using the same testing procedure and guidelines on result interpretation). Nevertheless, irrespective of the sources of uncertainty, the overall uncertainty can be estimated when the deduced lengths are compared with the as-built lengths.

The two types of grout pipes and conventional wires have been installed on 516 soil nails. These 516 soil nails are spread over 9 different LPM sites. Out of these 516 soil nails, 328 were assembled with Type 1 grout pipes and 188 soil nails were assembled with Type 2 grout pipes. Conventional wires were installed in all soil nails to benchmark the performance of the new grout pipes. Based on the field data, 4.9 % (16 nos.) of soil nails with Type 1 grout pipes were found to be defective (14 soil nails had defect in either copper wire and 2 soil nails had defect in both copper wires) whereas 4.3 % (8 nos.) of soil nails with Type 2 grout pipes were found to be defective (8 soil nails had defect in either copper wire). A total of four soil nails with conventional wires were also reported to be defective (the corresponding grout pipes were also defective), amount to about 1 % of all the nails. Excluding those soil nails with defective grout pipes or conventional wires, the data set contains measurements on 492 soil nails.

4.3.2 Interpretation of Test Results

The overall uncertainty of TDR test using the grout pipes with embedded copper wires have been estimated by comparing the estimated lengths with the as-built lengths of the 492

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soil nails. The frequency distributions of the length difference for Type 1 grout pipe, Type 2 grout pipe and the corresponding set of conventional wires are presented in Figures 1 and 2 respectively. The data sets are observed to fit a normal distribution, and they are not rejected by the Kolmogorov-Smirnov goodness-of-fit tests at the 5 % significance level (Ang & Tang, 2006). By fitting the probability distributions of the length difference with normal models, as in Figures 1 and 2, the means and standard deviations of the models are respectively found to be 1.43 % and 3.18 % for Type 1 grout pipes and –1.00 % and 6.59 % for the conventional wires in the same batch of soil nails, 0.23 % and 3.19 % for Type 2 grout pipes and –2.77 % and 5.22 % for the wires in the same batch of soil nails. This suggests that there is a 95 % confidence level that the difference in length between the estimated value and as-built value due to overall uncertainty falls within –4.8 % to +7.7 % for Type 1 grout pipes, –13.9 % to +11.9 % for the corresponding conventional wires, –6.0 % to +6.5 % for Type 2 grout pipes and –13.0 % to +7.5 % for the corresponding conventional wires. A summary of the results in given in Table 5.

5. SOIL NAILS PROTECTED BY CORRUGATED PLASTIC SHEATHING

Soil nails may be installed within corrugated plastic sheathing as measures against corrosive environment with the grout pipes installed outside the sheathing. In order to examine the feasibility of using the new grout pipe for TDR test, a total of 152 soil nails were installed with these grout pipes fixed on the outside of the plastic sheathing in two LPM sites. The defect rate is found to be 2 % (3 grout pipes had defect in either copper wire) for Type 1 grout pipe and 0 % (no defective wire) for the conventional wires. The 95 % confidence level that the difference in length between the estimated value and as-built value due to overall uncertainty falls within –9.1 % to +4.8 % for Type 1 grout pipes and –10.9 % to +7.6 % for the corresponding conventional wires. The results indicate that the defect rate and overall uncertainty are comparable with those without the corrugated plastic sheathing. A summary of the results is given in Table 5.

6. DISCUSSION AND CONCLUSION

The performance of the newly developed grout pipe with embedded copper wires for TDR test has been studied and benchmarked with that of the conventional wire. The benchmarking includes a precision experiment using prefabricated soil nails and working soil nails at 11 LPM sites (including two with corrugated plastic sheathing). In respect of grouting operation, the performance of the two types of new grout pipes is similar to that for the conventional grout pipe without embedded copper wires.

The cost of the grout pipe with embedded copper wires is about two to three times of that of the ordinary grout pipe (i.e. the one without the embedded copper wires). Nevertheless, the cost only constitutes a very small percentage of the total cost of a soil nail. It is expected that the cost of the new grout pipe will be further reduced as they become more common and manufactured in bulk quantity.

Precision experiment has revealed that the single-operator and multi-operator uncertainties of TDR tests using grout pipe with embedded copper wires are in general smaller than those using the conventional wire. It is mainly due to the phenomenon that the

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embedded copper wires can produce a relatively more distinct and sharp reflection in the TDR waveform that that in the conventional wire (see Figure 3). It enhances the consistency and hence the precision of the interpreted pulse travel times both within and between operators.

Similar for both types of new grout pipes and conventional wire, higher single and multi-operator uncertainties are in general observed in those measurements taken from soil nails of shorter length. This substantiates the choice of the longest soil nail among the test soil nails for calibration test because for a given testing instrument, the resolution on the interpreted travel time of a pulse along a long soil nail is comparatively higher than that for a short one. The overall uncertainty of TDR tests using grout pipe with embedded wires is also found to be smaller than that of using conventional wire. The smaller overall uncertainty associated with the use of grout pipe with embedded wires is partly attributed by the reduction in the uncertainty of human judgement.

The grout pipe with embedded copper wires seems to have a relatively higher material defect rate than that of the conventional wire. In all, the use of grout pipe with embedded copper wires is found to be feasible for both the grouting works and TDR test.

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Table 1 - TDR Test Results of Prefabricated Soil Nail No. 1 (6 m)

Operator	Type 1 Grout Pipe							Type 2 Grout Pipe[1]							Conventional Wire						
	Interpreted Time of Travel (*ns*) Round					Mean μ (*ns*)	Standard Deviation σ (*ns*)	Interpreted Time of Travel (*ns*) Round					Mean μ (*ns*)	Standard Deviation σ (*ns*)	Interpreted Time of Travel (*ns*) Round					Mean μ (*ns*)	Standard Deviation σ (*ns*)
	1st	2nd	3rd	4th	5th			1st	2nd	3rd	4th	5th			1st	2nd	3rd	4th	5th		
1	92.8	94.0	94.2	93.2	94.2	93.7	0.66	-	-	-	-	-	-	-	143.2	148.9	148.8	146.8	144.4	146.4	2.57
2	92.7	89.8	93.6	89.5	89.6	91.0	1.97	-	-	-	-	-	-	-	137.8	127.7	128.5	132.3	139.2	133.1	5.25
3	90.7	90.3	89.2	89.1	88.7	89.6	0.83	-	-	-	-	-	-	-	130.0	128.2	128.9	128.2	128.4	128.7	0.76
4	92.1	92.7	90.8	92.5	90.2	91.6	1.08	-	-	-	-	-	-	-	136.3	145.1	141.8	144.2	141.4	141.8	3.43
5	92.9	93.4	92.7	92.5	93.3	92.9	0.38	-	-	-	-	-	-	-	144.5	145.8	145.3	145.7	146.1	145.5	0.62
6	91.0	90.2	89.8	89.5	90.8	90.2	0.66	-	-	-	-	-	-	-	132.7	136.5	134.0	140.1	135.4	135.7	2.83
7	94.1	93.4	93.6	93.0	94.1	93.6	0.50	-	-	-	-	-	-	-	147.3	142.2	145.4	144.6	145.8	145.1	1.88
8	92.0	90.9	89.6	90.2	91.2	90.8	0.95	-	-	-	-	-	-	-	140.3	138.2	133.6	136.1	131.6	136.0	3.48
9	91.3	93.9	91.1	92.2	91.6	92.0	1.13	-	-	-	-	-	-	-	139.3	175.6[2]	141.7	142.5	145.1	142.2	2.39
10	91.9	92.0	91.8	92.0	91.7	91.8	0.14	-	-	-	-	-	-	-	140.8	141.7	142.1	143.8	142.8	142.2	1.13
11	92.6	93.3	92.6	93.6	92.8	92.9	0.45	-	-	-	-	-	-	-	144.8	145.2	142.4	142.2	145.0	143.9	1.49
12	88.8	89.7	91.1	91.0	91.1	90.3	1.07	-	-	-	-	-	-	-	139.0	142.6	143.1	144.7	143.6	142.6	2.16
13	92.1	92.5	91.4	91.7	93.5	92.2	0.83	-	-	-	-	-	-	-	141.1	140.8	144.6	144.1	143.6	142.8	1.76
14	93.2[2]	91.8	92.0	92.2	91.9	91.9	0.17	-	-	-	-	-	-	-	138.3	136.3	136.7	135.6	136.3	136.6	1.01
15	89.4	90.2	89.5	90.3	89.2	89.7	0.49	-	-	-	-	-	-	-	132.0	132.5	131.4	132.7	132.7	132.3	0.56
16	91.9	92.2	94.2	92.3	92.8	92.6	0.91	-	-	-	-	-	-	-	136.3	143.4	141.1	143.8	141.7	141.3	2.99
17	92.2	92.9	93.6	92.9	93.5	93.0	0.57	-	-	-	-	-	-	-	142.2	148.5	148.3	146.8	144.6	146.1	2.67
18	90.4	93.3	90.8	91.2	91.2	91.3	1.12	-	-	-	-	-	-	-	132.3	133.6	134.5	137.1	132.8	134.1	1.89
General Mean, m (*ns*)							91.7							-							139.77
Repeatability (Single-operator) Standard Deviation, s_r (*ns*)							0.89							-							2.46
Reproducibility (Multi-operator) Standard Deviation, s_R (*ns*)							1.50							-							5.84
95% Confidence Level Uncertainty of Repeatability SD[3], A_r							0.16							-							0.16
95% Confidence Level Uncertainty of Reproducibility SD[3], A_R							0.25							-							0.29
Coefficient of Variation (*c.o.v.*) of Single-operator (%)							1.0							-							1.8
95% Confidence Level Range of *c.o.v.* of Single-operator (%)							0.8 - 1.2							-							1.5 - 2.1
Coefficient of Variation (*c.o.v.*) of Multi-operator (%)							1.6							-							4.2
95% Confidence Level Range of *c.o.v.* of Multi-operator (%)							1.3 - 2.2							-							3.2 - 5.9

Notes: (1) No signal was received from Wire C.
(2) Data classified as outlier by Grubb's Test (BSI, 1994a).
(3) SD: Standard deviation

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Table 2 - TDR Test Results of Prefabricated Soil Nail No. 2 (12 m)

Operator	Type 1 Grout Pipe							Type 2 Grout Pipe							Conventional Wire						
	Interpreted Time of Travel (*ns*)					Mean μ (*ns*)	Standard Deviation σ (*ns*)	Interpreted Time of Travel (*ns*)					Mean μ (*ns*)	Standard Deviation σ (*ns*)	Interpreted Time of Travel (*ns*)					Mean μ (*ns*)	Standard Deviation σ (*ns*)
	Round							Round							Round						
	1st	2nd	3rd	4th	5th			1st	2nd	3rd	4th	5th			1st	2nd	3rd	4th	5th		
1	182.6	182.0	183.0	184.3	183.0	183.0	0.86	215.3	215.5	216.5	216.5	217.2	216.2	0.81	284.4	283.4	285.6	285.7	286.3	285.1	1.16
2	180.2	179.2	179.2	178.9	*184.0*[(1)]	179.3	0.56	214.4	213.7	216.1	212.9	217.0	214.8	1.69	272.5	271.9	275.0	267.1	286.9	274.7	7.41
3	180.5	181.6	181.3	178.8	179.7	180.3	1.15	215.5	213.4	214.6	216.5	214.2	214.8	1.21	276.3	270.7	274.8	269.2	273.2	272.8	2.91
4	181.2	183.1	181.9	181.3	182.5	182.0	0.78	214.5	219.8	218.0	216.9	216.8	217.2	1.95	289.6	281.3	281.9	281.9	288.5	284.6	4.05
5	183.8	182.5	183.2	182.9	183.1	183.1	0.47	219.2	217.1	217.8	218.1	218.9	218.2	0.83	*293.8*[(1)]	282.7	281.4	280.4	281.3	281.5	0.95
6	179.7	181.9	181.2	181.9	181.7	181.3	0.95	216.3	220.3	218.6	218.9	218.6	218.5	1.44	278.8	280.7	281.9	280.2	283.4	281.0	1.74
7	183.7	182.4	182.0	180.4	184.3	182.5	1.55	218.9	217.3	216.5	217.3	220.0	218.0	1.42	286.1	*283.7*[(1)]	286.8	286.1	286.8	286.5	0.40
8	181.7	181.4	182.1	181.0	182.9	181.8	0.74	216.9	217.5	217.1	216.7	217.2	217.1	0.28	279.4	278.8	280.3	280.4	*288.3*[(1)]	279.7	0.76
9	183.1	182.9	183.8	183.5	184.2	183.5	0.53	216.1	216.5	219.1	217.8	218.6	217.6	1.29	283.4	287.1	287.2	286.3	279.0	284.6	3.49
10	182.6	183.1	183.1	183.1	183.9	183.1	0.45	217.9	217.1	217.6	216.9	217.4	217.4	0.41	283.4	287.0	284.0	285.6	289.4	285.9	2.42
11	185.0	181.3	180.6	181.9	182.2	182.2	1.70	*224.7*[(1)]	215.5	214.0	212.8	214.9	214.3	1.15	287.1	276.7	280.2	276.7	282.0	280.5	4.32
12	181.2	183.9	184.6	184.3	183.3	183.4	1.37	212.5	212.5	213.8	214.9	211.2	213.0	1.41	274.9	277.0	276.2	275.6	275.6	275.9	0.79
13	181.2	181.8	182.8	183.2	182.9	182.4	0.83	*215.4*[(1)]	218.7	217.9	218.2	218.3	218.3	0.35	278.8	276.6	277.8	277.3	273.9	276.9	1.85
14	181.3	180.6	181.4	181.2	181.6	181.2	0.38	215.8	215.2	215.4	215.4	215.6	215.4	0.23	281.7	280.9	281.7	280.9	282.5	281.5	0.67
15	180.9	181.3	181.5	181.3	181.2	181.2	0.24	214.2	214.3	213.4	212.2	213.2	213.4	0.85	279.6	277.8	279.6	278.7	278.8	278.9	0.75
16	180.8	182.0	183.0	182.6	184.8	182.6	1.48	214.1	216.9	215.4	218.5	218.3	216.6	1.87	283.0	283.9	286.6	280.0	283.9	283.5	2.37
17	*193.4*[(1)]	179.8	181.1	181.6	180.5	180.7	0.78	213.0	213.0	210.9	212.8	211.8	212.3	0.91	294.7	280.9	282.1	287.6	287.2	286.5	5.47
18	*183.2*[(1)]	181.2	181.2	181.0	181.4	181.2	0.17	210.9	211.3	211.6	211.6	212.7	211.6	0.66	276.1	273.2	279.4	276.8	279.6	277.0	2.64
General Mean, m (*ns*)							182.0							215.8							280.9
Repeatability (Single-operator) Standard Deviation, s_r (*ns*)							0.96							1.17							3.14
Reproducibility (Multi-operator) Standard Deviation, s_R (*ns*)							1.41							2.43							5.10
95% Confidence Level Uncertainty of Repeatability SD[(2)], A_r							0.16							0.16							0.16
95% Confidence Level Uncertainty of Reproducibility SD[(2)], A_R							0.22							0.28							0.24
Coefficient of Variation (*c.o.v.*) of Single-operator (%)							0.5							0.5							1.1
95% Confidence Level Range of *c.o.v.* of Single-operator (%)							0.5 - 0.6							0.5 - 0.6							1.0 - 1.3
Coefficient of Variation (*c.o.v.*) of Multi-operator (%)							0.8							1.1							1.8
95% Confidence Level Range of *c.o.v.* of Multi-operator (%)							0.6 - 1.0							0.9 - 1.6							1.5 - 2.4

Notes: (1) Data classified as outlier by Grubb's Test (BSI, 1994a).
(2) SD: Standard deviation

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Table 3 - TDR Test Results of Prefabricated Soil Nail No. 3 (20 m)

Operator	Type 1 Grout Pipe							Type 2 Grout Pipe(1)							Conventional Wire						
	Interpreted Time of Travel (*ns*)					Mean μ (*ns*)	Standard Deviation σ (*ns*)	Interpreted Time of Travel (*ns*)					Mean μ (*ns*)	Standard Deviation σ (*ns*)	Interpreted Time of Travel (*ns*)					Mean μ (*ns*)	Standard Deviation σ (*ns*)
	Round							Round							Round						
	1st	2nd	3rd	4th	5th			1st	2nd	3rd	4th	5th			1st	2nd	3rd	4th	5th		
1	317.5	316.9	316.5	316.3	316.3	316.7	0.49	-	-	-	-	-	-	-	466.4	471.7	471.3	468.0	468.4	469.2	2.27
2	313.0	314.8	316.3	314.8	315.3	314.8	1.18	-	-	-	-	-	-	-	453.0	458.2	461.2	465.2	455.4	458.6	4.80
3	311.8	310.9	310.2	310.5	311.8	311.0	0.74	-	-	-	-	-	-	-	454.4	452.4	446.6	446.9	459.1	451.9	5.28
4	315.2	315.6	316.6	316.1	316.2	315.9	0.55	-	-	-	-	-	-	-	474.8	474.3	484.1	476.3	481.3	478.2	4.32
5	313.8	314.7	314.9	313.7	314.9	314.4	0.60	-	-	-	-	-	-	-	468.2	476.5	471.2	471.2	475.9	472.6	3.51
6	313.3	316.2	313.2	314.8	316.3	314.7	1.53	-	-	-	-	-	-	-	480.3	471.1	478.3	482.2	473.5	477.1	4.65
7	316.4	315.9	316.0	315.2	318.3	316.3	1.18	-	-	-	-	-	-	-	485.7	472.3	481.7	473.9	479.4	478.6	5.53
8	311.3	312.9	310.4	314.1	313.1	312.3	1.49	-	-	-	-	-	-	-	473.3	466.7	471.8	466.5	476.4	470.9	4.30
9	312.2	313.9	314.0	313.3	313.5	313.4	0.72	-	-	-	-	-	-	-	460.5	475.0	465.9	461.6	473.8	467.4	6.75
10	315.1	314.8	316.1	314.9	315.5	315.2	0.53	-	-	-	-	-	-	-	465.7	466.4	474.2	464.7	478.5	469.9	6.11
11	313.7	314.6	314.7	314.3	313.7	314.2	0.47	-	-	-	-	-	-	-	464.9	467.5	463.3	467.1	466.2	465.8	1.72
12	314.4	312.5	313.2	314.1	313.4	313.5	0.75	-	-	-	-	-	-	-	457.7	461.7	467.2	467.4	466.0	464.0	4.21
13	316.4	312.7	314.5	314.9	313.8	314.4	1.38	-	-	-	-	-	-	-	464.6	473.6	468.8	471.8	474.8	470.7	4.10
14	314.4	315.2	316.3	315.0	314.6	315.1	0.76	-	-	-	-	-	-	-	477.4	480.6	464.8	471.1	468.0	472.4	6.54
15	314.4	314.2	314.1	314.9	314.1	314.3	0.32	-	-	-	-	-	-	-	449.9	454.1	454.2	451.6	454.4	452.8	2.00
16	315.1	316.7	315.2	316.1	317.9	316.2	1.15	-	-	-	-	-	-	-	469.4	477.6	475.4	472.9	475.0	474.1	3.09
17	314.8	314.0	313.8	314.4	314.7	314.3	0.43	-	-	-	-	-	-	-	464.0	*470.3*(2)	463.7	462.1	462.1	463.0	1.02
18	313.0	315.5	312.4	315.0	314.1	314.0	1.31	-	-	-	-	-	-	-	462.5	447.3	468.6	471.0	454.4	460.8	9.89
General Mean, m (*ns*)							314.5							-							467.7
Repeatability (Single-operator) Standard Deviation, s_r (*ns*)							0.95							-							4.94
Reproducibility (Multi-operator) Standard Deviation, s_R (*ns*)							1.64							-							9.11
95% Confidence Level Uncertainty of Repeatability SD(3), A_r							0.16							-							0.16
95% Confidence Level Uncertainty of Reproducibility SD(3), A_R							0.25							-							0.26
Coefficient of Variation (*c.o.v.*) of Single-operator (%)							0.3							-							1.1
95% Confidence Level Range of *c.o.v.* of Single-operator (%)							0.3 - 0.4							-							0.9 - 1.3
Coefficient of Variation (*c.o.v.*) of Multi-operator (%)							0.5							-							1.9
95% Confidence Level Range of *c.o.v.* of Multi-operator (%)							0.4 - 0.7							-							1.5 - 2.6

Notes: (1) No signal was received from Wire C.
(2) Data classified as outlier by Grubb's Test (BSI, 1994a).
(3) SD: Standard deviation

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Table 4 - Summary of Human Uncertainty

Prefabricated Soil Nail		Coefficient of Variation at 95 % Confidence Level	
		Single-operator Uncertainty	Multi-operator Uncertainty
No. 1 (6 m)	Type 1 Grout Pipe	0.8 % - 1.2 %	1.3 % - 2.2 %
	Type 2 Grout Pipe	-	-
	Conventional Wire	1.5 % - 2.1 %	3.2 % - 5.9 %
No. 2 (12 m)	Type 1 Grout Pipe	0.5 % - 0.6 %	0.6 % - 1.0 %
	Type 2 Grout Pipe	0.5 % - 0.6 %	0.9 % - 1.6 %
	Conventional Wire	1.0 % - 1.3 %	1.5 % - 2.4 %
No. 3 (20 m)	Type 1 Grout Pipe	0.3 % - 0.4 %	0.4 % - 0.7 %
	Type 2 Grout Pipe	-	-
	Conventional Wire	0.9 % - 1.3 %	1.5 % - 2.6 %

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Table 5 - Summary of Overall Uncertainty

Site		Overall Uncertainty		
		Mean	Standard Deviation	95 % Confidence Level Range
7SW-C/C115 Wo Yi Hop Road 6SE-C/C481 Ting Kau Village 7SW-C/C862 & C884 Shing Mun Road 7SW-C/C271 Kwan Mun Hau Tsuen 6SE-C/C322 Sham Tseng San Tsuen	Type 1 Grout Pipe	1.43 %	3.18 %	–4.8 % - +7.7 %
	Conventional Wire	–1.00 %	6.59 %	–13.9 % - +11.9 %
11NE-B/C533 Nam Wai 12NW-C/C276 Hang Hau 6SW-A/C303 Tseng Tau Chung Tsuen 7SW-C/C271 Kwan Mun Hau Tsuen	Type 2 Grout Pipe	0.23 %	3.19 %	–6.0 % - +6.5 %
	Conventional Wire	–2.77 %	5.22 %	–13.0 % - +7.5 %
6SW-B/C221 Pun Shan Tsuen 7SW-C/C601 Yuen Yuen Care and Attention Home	Type 1 Grout Pipe with Corrugated Plastic Sheathing	–2.15 %	3.53 %	–9.1 % - +4.8 %
	Conventional Wire with Corrugated Plastic Sheathing	–1.65 %	4.72 %	–10.9 % - +7.6 %

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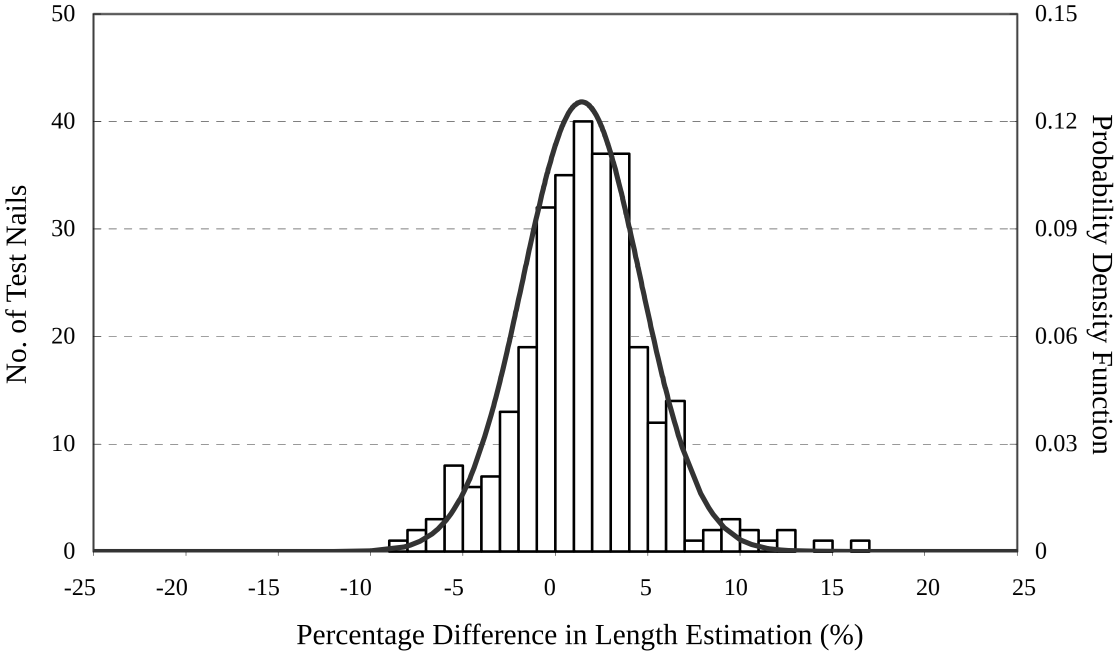
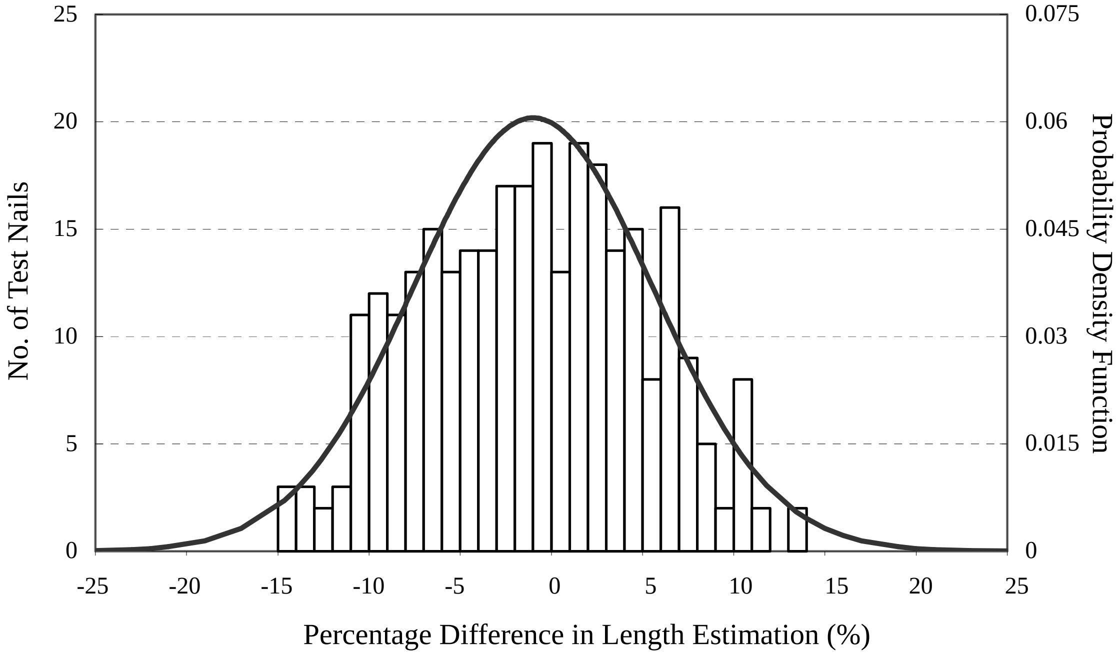


(a) Frequency Distribution and Probability Density Function of Estimation Error for Type 1 Grout Pipe



(b) Frequency Distribution and Probability Density Function of Estimation Error for the Corresponding Set of Conventional Wires

Note: $$\%\ \text{Difference in Length Estimation} = \frac{\text{Estimated nail length - As-built nail length}}{\text{As-built nail length}}$$

Figure 1 - Overall Uncertainty of TDR Test using Type 1 Grout Pipe and Conventional Wire

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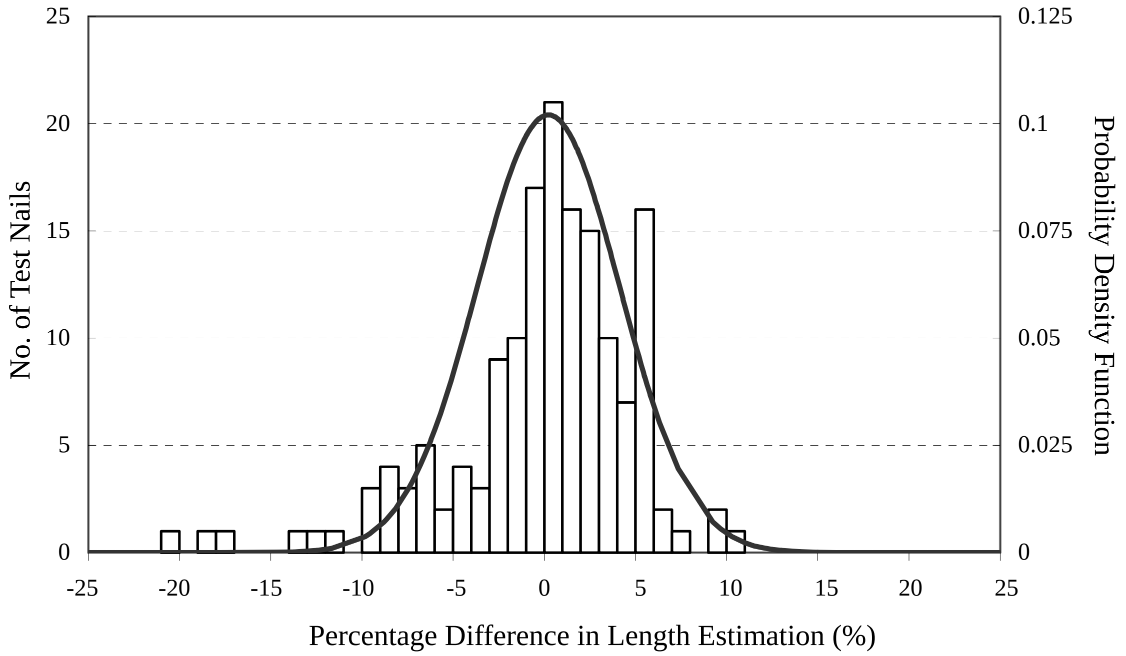
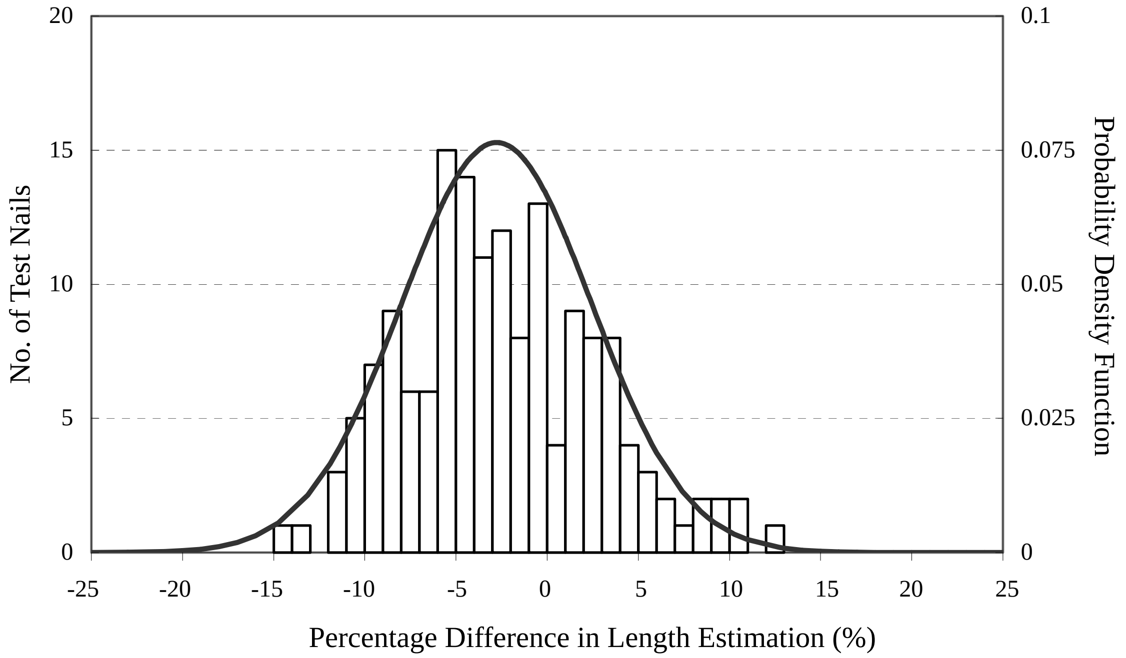


(a) Frequency Distribution and Probability Density Function of Estimation Error for Type 2 Grout Pipe



(b) Frequency Distribution and Probability Density Function of Estimation Error for the Corresponding Set of Conventional Wires

Note: $$\%\ \text{Difference in Length Estimation} = \frac{\text{Estimated nail length - As-built nail length}}{\text{As-built nail length}}$$

Figure 2 - Overall Uncertainty of TDR Test using Type 2 Grout Pipe and Conventional Wire

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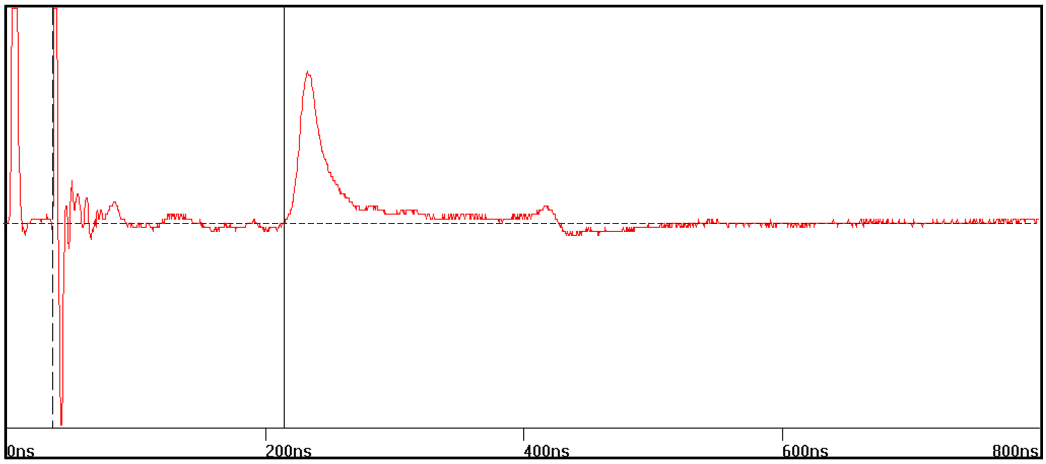
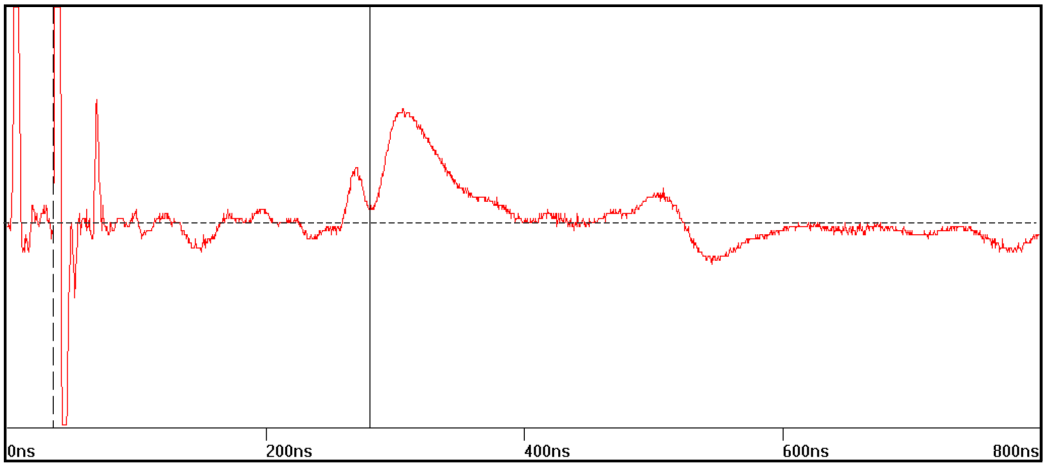
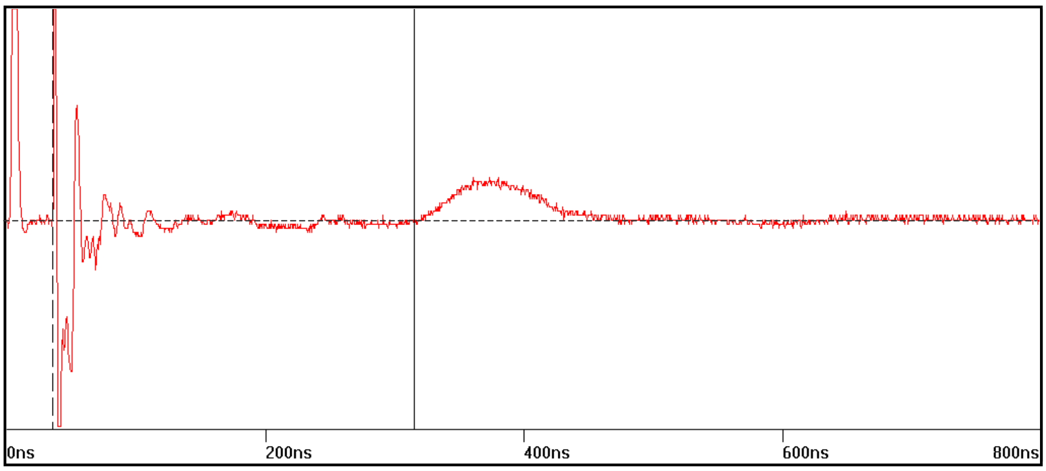


(a) Typical TDR Waveform (Single Peak) of Embedded Copper Wire in Grout Pipe



(b) Typical TDR Waveform (Multiple Peaks) of Embedded Copper Wire in Grout Pipe



(c) Typical TDR Waveform of Conventional Wire

Figure 3 - TDR Waveforms of Embedded Copper Wire in Grout Pipe and Conventional Wire

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LIST OF PLATES

Grout Pipe (Type 1)

Grout Pipe (Type 2)

Plate 1 - Grout Pipes with Embedded Copper Wires

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APPENDIX A

GUIDELINES ON TESTING PROCEDURE AND INTERPRETATION OF TEST RESULTS USING TIME DOMAIN REFLECTOMETRY (TDR) ON GROUT PIPES WITH EMBEDDED COPPER WIRES TO DETERMINE THE LENGTH OF INSTALLED SOIL NAILS

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Guidelines on Testing Procedure and Interpretation of Test Results Using Time Domain Reflectometry (TDR) on Grout Pipes with Embedded Copper Wires to Determine the Length of Installed Soil Nails

1. General

1.1 A grout pipe with embedded copper wires shall be installed alongside the steel reinforcement with details shown in Figure A1. The grout pipe shall be terminated at a point above the lower end of the steel reinforcement as specified in the figure.

1.2 TDR measurements shall be conducted on both copper wires using two distinct pulse widths, one less than 5 nanoseconds (*ns*) and one greater than 5*ns*.

2. Preparation for TDR tests

2.1 No TDR test shall be carried out on a soil nail within one day after the completion of grouting.

2.2 The head of the steel reinforcement and the embedded copper wires shall be electrically accessible. All loose materials shall be removed from the exposed portion of the steel reinforcement and the embedded copper wire so that good electrical contact to the test lead of the TDR equipment can be made.

3. Testing Procedures and Interpretation of Test Results

3.1 Determination of Reference Pulse Propagation Velocity

3.1.1 In the TDR tests, a Reference Pulse Propagation Velocity, v_r is used to deduce the length of test soil nails. The Reference Pulse Propagation Velocity can be applied to determine the length of other soil nails (different lengths and diameters) with the same type of grout pipe with embedded copper wires and the same approved grout mix. The Reference Pulse Propagation Velocity shall be the average pulse propagation velocity from a minimum of three calibration soil nails.

3.1.2 Select three soil nails of known lengths for determination of the Reference Pulse Propagation Velocity. If soil nails of different lengths and different bar diameters are available for testing, the longest three soil nails of any bar diameter shall be selected for calibration.

3.1.3 In case the waveforms of a selected soil nail are atypical, e.g. presence of significant ripples before the major pulse reflection, or inverted major pulse reflection (see Figure A2 for examples), it shall not be used as a calibration soil nail and a different soil nail shall be selected for calibration. The one that has atypical waveform shall be treated as a test soil nail and its length be deduced in accordance with Section 3.2 below.

3.1.4 Separate calibration soil nails shall be selected for soil nails with different type of grout pipe embedded with copper wires.

3.1.5 With the clips of the test lead unconnected as in Figure A3(a), move line '1' on the

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display panel of the TDR equipment to the position where the reflected pulse corresponding to the clips starts to rise. The correctness of the position of line '1' should be confirmed by connecting the clips. When the clips are connected, the polarity of the pulse at line '1' would be reversed as indicated in Figure A3(b).

3.1.6 Connect the clips to the calibration soil nail as shown in Figure A3(c); one to the steel reinforcement and the other to one of the embedded copper wire.

3.1.7 Identify the pulse reflected from the end of the test soil nail, and move line '2' to the position where the pulse starts to rise. The recorded waveform usually shows a number of reflected pulses with small amplitude followed by one with considerably larger amplitude. Move line '2' to the one with the largest amplitude (see Figure A3(c)).

3.1.8 Record the time of travel between line '1' and line '2', and the waveform.

3.1.9 Repeat the procedures in Sections 3.1.5 to 3.1.8 using a different pulse width as specified in Section 1.2.

3.1.10 Among the measurements taken with pulses of different widths, select those with a clear and distinct reflection for calculating the average travel time of pulse in copper wire, t_{c1}.

3.1.11 Repeat the procedures in Sections 3.1.5 to 3.1.10 using the other embedded copper wire and obtain the average value of time of travel, t_{c2}.

3.1.12 Determine the average time of travel, t_c, using Equation (1).

$$t_c = \frac{t_{c1} + t_{c2}}{2} \qquad (1)$$

3.1.13 Determine the pulse propagation velocity, v_p, of a calibration soil nail using Equation (2a).

$$v_p = \frac{2(L_d - S_b)}{t_c} \qquad (2a)$$

where L_d is the design length of soil nail, S_b is the amount of set back of the grout pipe from the lower end of the steel reinforcement, t_c is the average time of travel between line '1' and line '2', which corresponds to the time for the pulse to travel from the head of soil-nail reinforcement to its end and back to the head, i.e. 2 times the soil-nail length.

Some TDR instruments make allowance for the travel time of the pulse and the time shown on the display panel actually corresponds to one soil-nail length. In such case, Equation (2b) should be used to determine the average pulse propagation velocity. Users should refer to the specification of their TDR instrument to check which

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equation is to be used.

$$v_p = \frac{L_d - S_b}{t_c} \qquad (2b)$$

3.1.14 Repeat the procedures in Sections 3.1.5 to 3.1.13 to obtain the pulse propagation velocity of all three calibration soil nails selected. The Reference Pulse Propagation Velocity, v_r shall be taken as the average pulse propagation velocity measured in the three calibration soil nails.

3.2 Determination of the Length of Soil Nails

3.2.1 The average travel time of the pulse along the soil nail, *t*, shall be determined for all soil nails to be tested by TDR based on the procedures given in Sections 3.1.5 to 3.1.12.

3.2.2 Deduce the length of each soil nail, L_i, using either Equation (3a) or (3b) as appropriate.

$$L_i = \frac{v_r t}{2} + S_b \qquad (3a)$$

or

$$L_i = v_r t + S_b \qquad (3b)$$

3.2.3 The presence of small amplitude reflections may obscure the identification of the pulse reflected from the soil-nail end. Procedures to identify the rise of the largest reflected pulse in these cases are shown in Figure A4. In some cases, the recorded waveforms may display multiple peaks, and the procedures to determine the time of travel for those soil nails are shown in Figure A5.

4. Worked Example

4.1 Determination of the Pulse Propagation Velocity in Calibration Soil Nail

Three calibration soil nails were selected for the determination of the Referenced Pulse Propagation Velocity. One of the calibration soil nails was 7 m long (with grout pipe terminated at 0.15 m above the lower end of the steel reinforcement). Measurements were taken with two different pulse widths, and the results are shown in Figure A6. The pulse propagation velocity for this calibration soil nail, v_{p1}, is given by:

$$t_{c1} = \frac{122.8 + 129.5}{2} = 126.2\,ns$$

$$t_{c2} = \frac{116.5 + 116.9}{2} = 116.7\,ns$$

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$$t_c = \frac{126.2 + 116.7}{2} = 121.5\,ns$$

$$v_{p1} = \frac{2 \times (7 - 0.15)}{121.5} = 0.11276 \text{ m}/ns$$

The average pulse propagation velocities of the other two calibration soil nails, v_{p2} and v_{p3} are determined similarly. Assuming v_{p1} = v_{p2} = v_{p3} in this example, v_r is determined as :

$$v_r = \frac{(v_{p1} + v_{p2} + v_{P3})}{3} = 0.11276 \text{ m}/ns$$

4.2 Determination of the Length of Soil Nail

A soil nail of unknown length (with grout pipe terminated at 0.15 m above the lower end of the steel reinforcement) was tested using two different pulse widths. The results are shown in Figure A7. Based on v_r obtained from the calibration test, the length of the soil nail, L_i, is estimated to be:

$$t_1 = \frac{114.9 + 117.7}{2} = 116.3\,ns$$

$$t_2 = \frac{119.6 + 122.4}{2} = 121.0\,ns$$

$$t = \frac{116.3 + 121.0}{2} = 118.7\,ns$$

$$L_i = \frac{0.11276 \times 118.7}{2} + 0.15$$

$$= 6.8 \text{ m}$$

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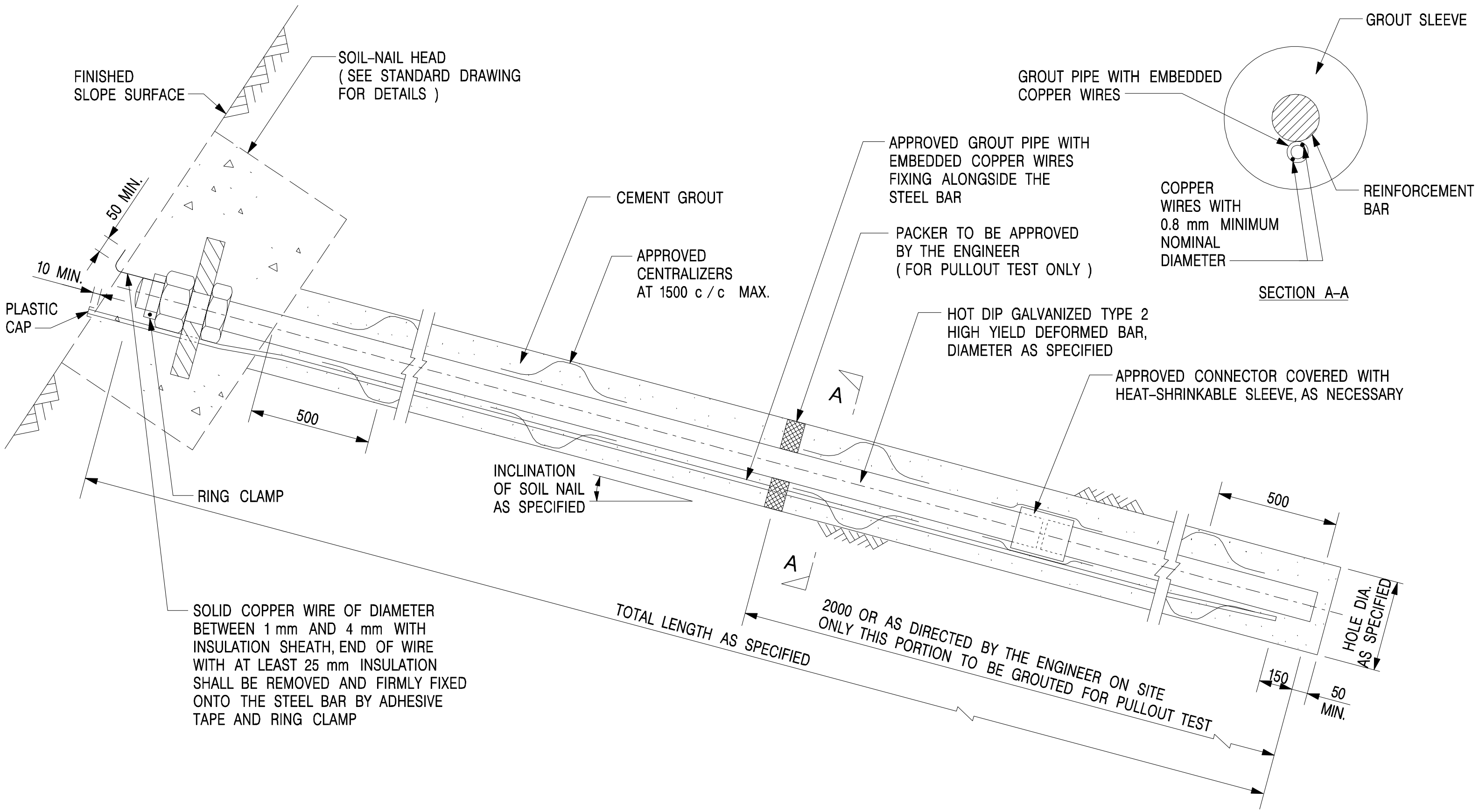

NOTES:

1. ALL DIMENSIONS ARE IN MILLIMETRES.
2. DRILLHOLE SHALL BE COMPLETELY FILLED WITH GROUT TO THE FINISHED SLOPE SURFACE.
3. MINIMUM GROUT COVER OF 20 mm SHALL BE PROVIDED TO THE BAR.
4. THE HEAT-SHRINKABLE SLEEVE SHALL BE OMITTED FOR SOIL NAILS UNDER PULLOUT TEST.

Figure A1 - Details of Provision of Grout Pipe with Embedded Copper Wires for Determination of Length of Soil-nail Reinforcement Using Time Domain Reflectometry

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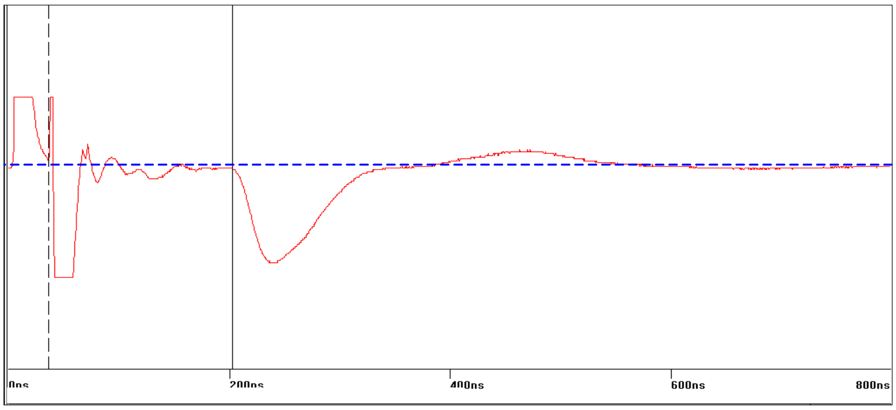
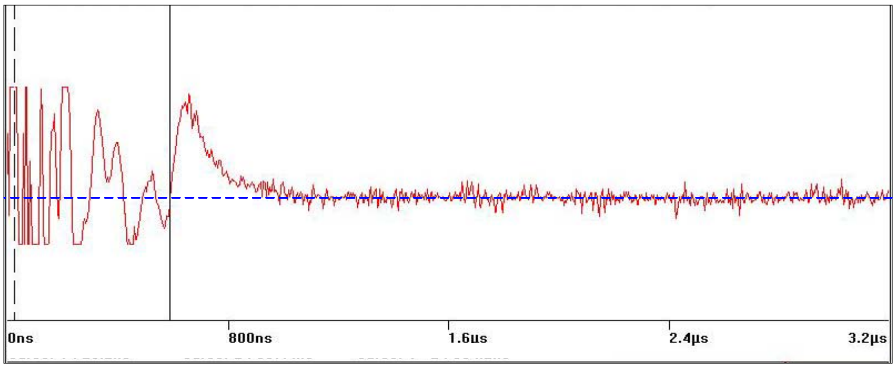
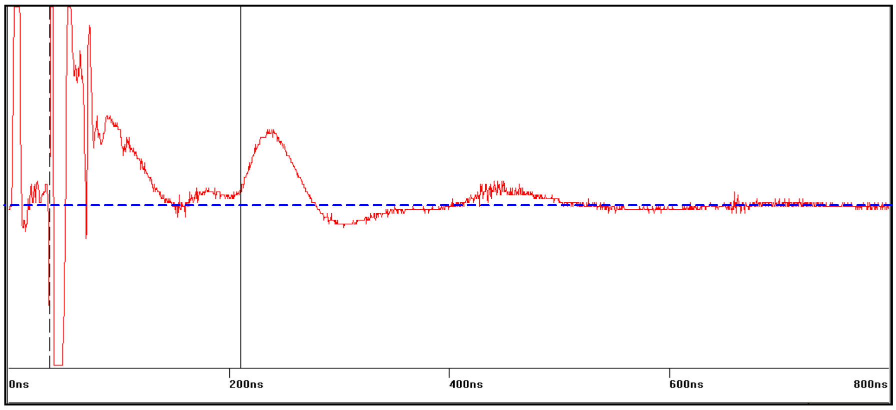


(a) Inverted Major Reflection



(b) Significant Ripples before Major Reflection



(c) Significant Ripples before Major Reflection

Figure A2 - Examples of Atypical TDR Waveforms

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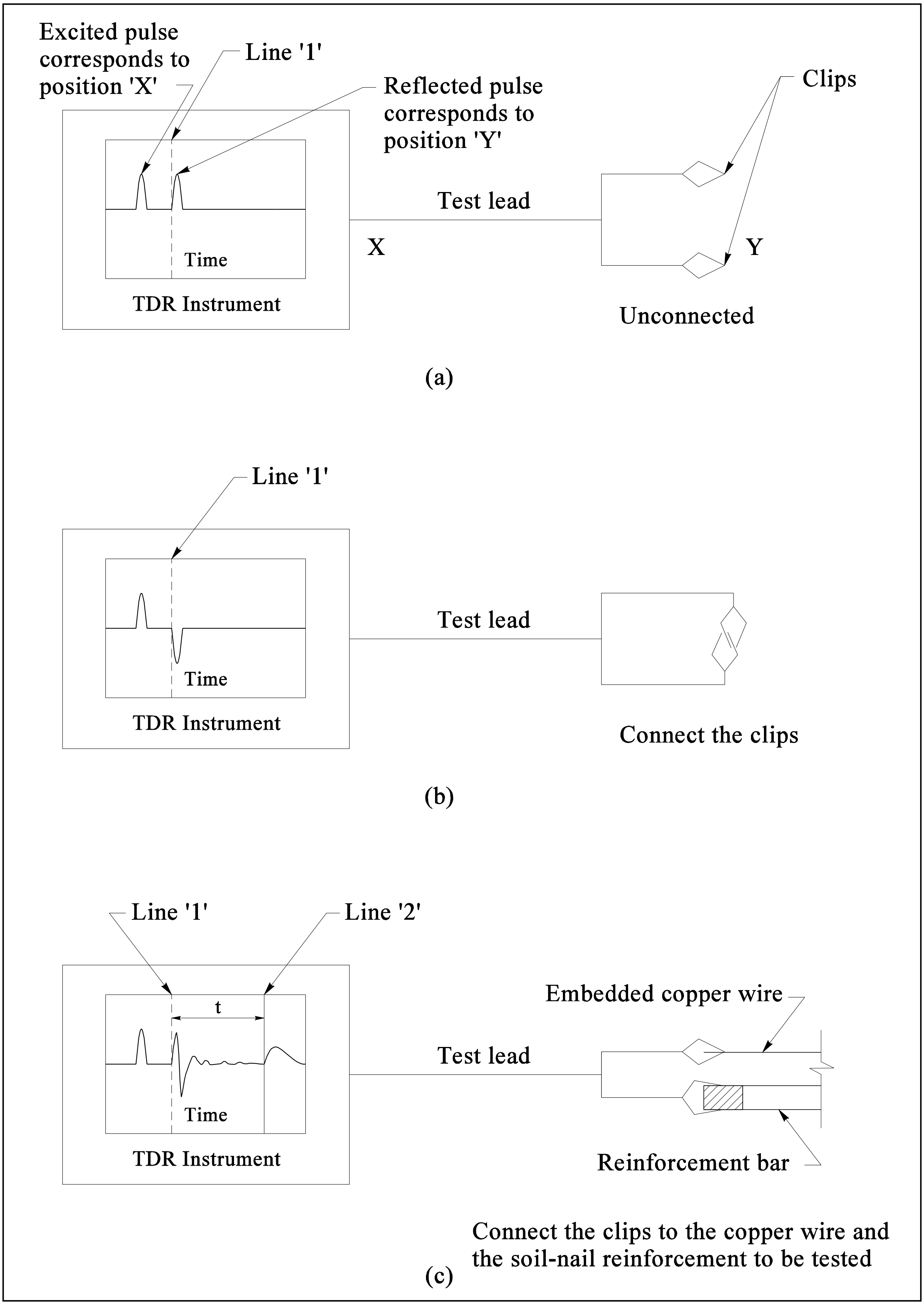
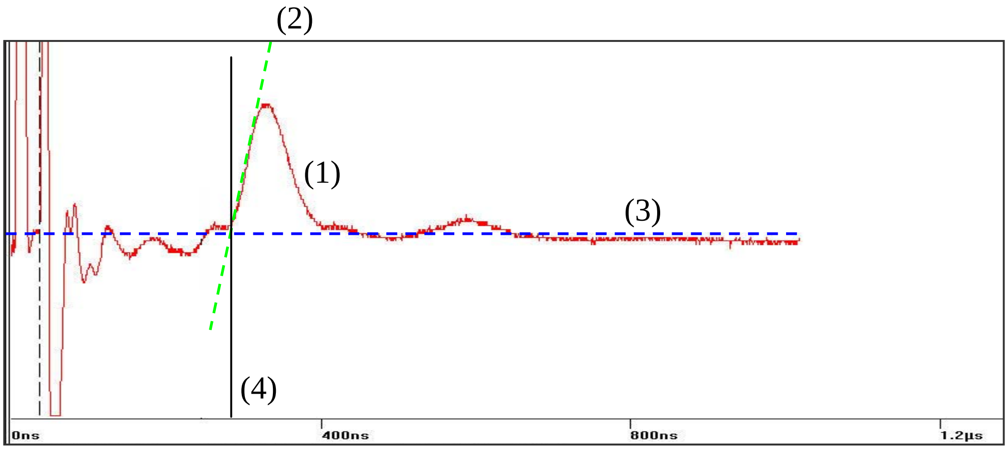


Figure A3 - Schematic Diagram Showing the Procedure of Using Time Domain Reflectometry for Determination of Length of Soil-nail Reinforcement

(1) Identify the largest reflected pulse
(2) Extend the left sloping side of the largest reflected pulse
(3) Extend the leveled tail part of the waveform
(4) Take the time of travel as the interception point of (2) and (3)

Example 1



Example 2

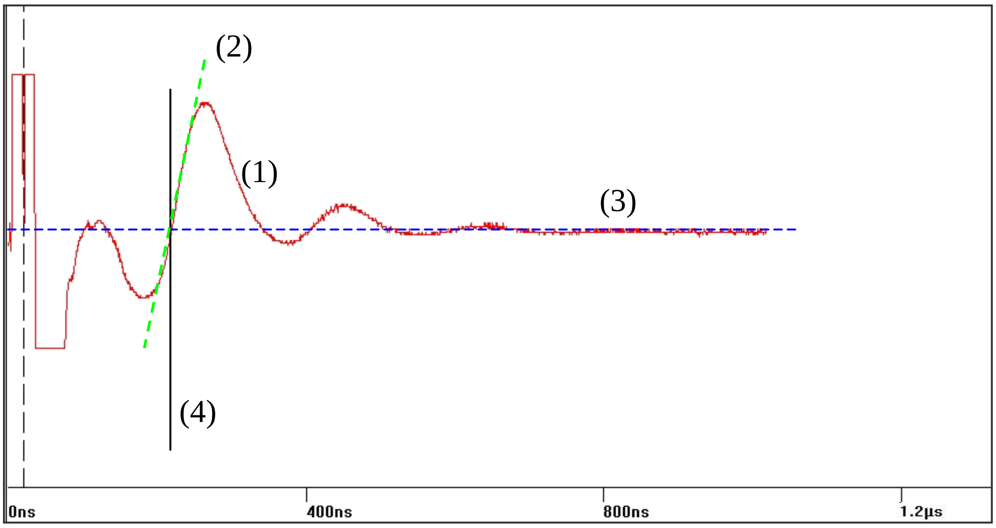


Figure A4 - Procedures to Identify the Rise of the Largest Reflected Pulse

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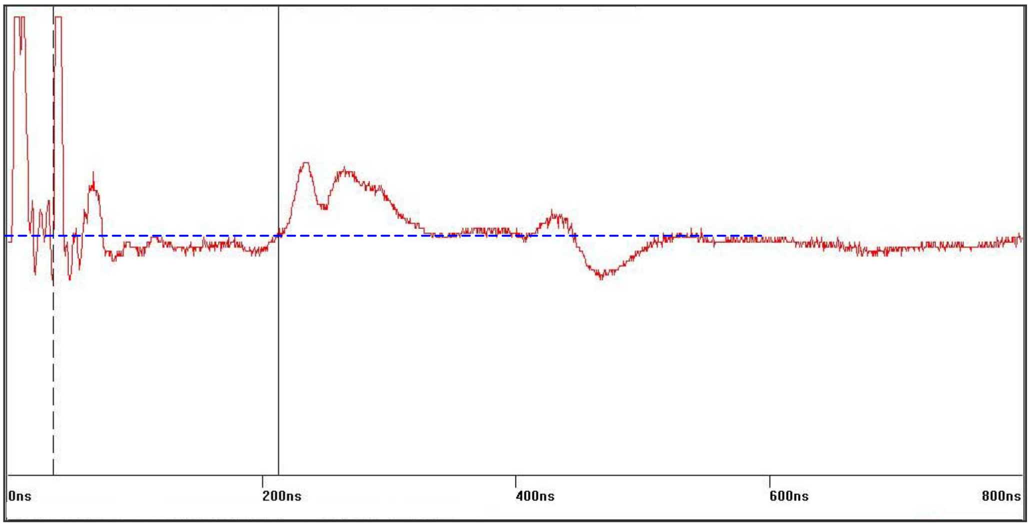
(a) <u>Example 1</u>

Reflected pulse with multiple peaks of similar amplitude – take the time of travel as the initial rise of the reflected pulse



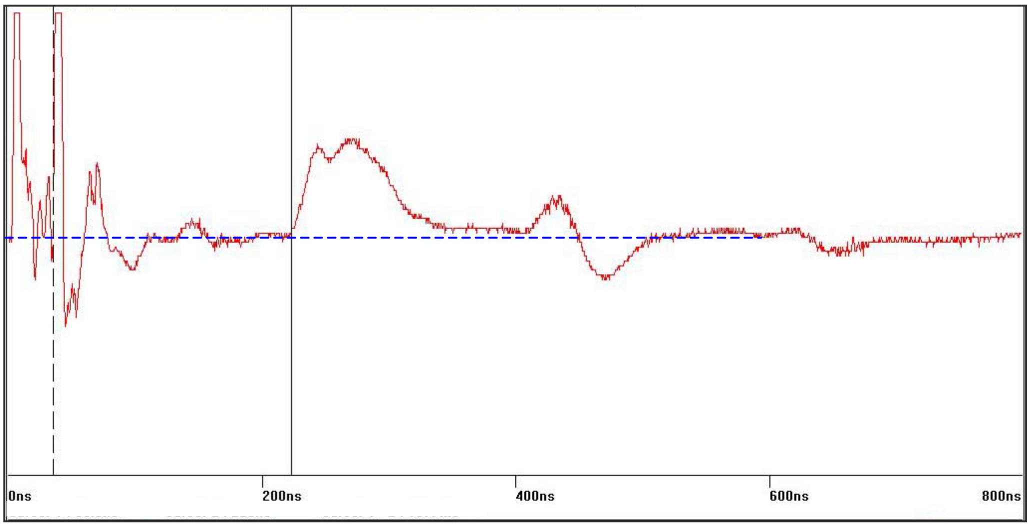


Figure A5 - Procedures to Identify the Rise of the Reflected Pulse with Multiple Peaks

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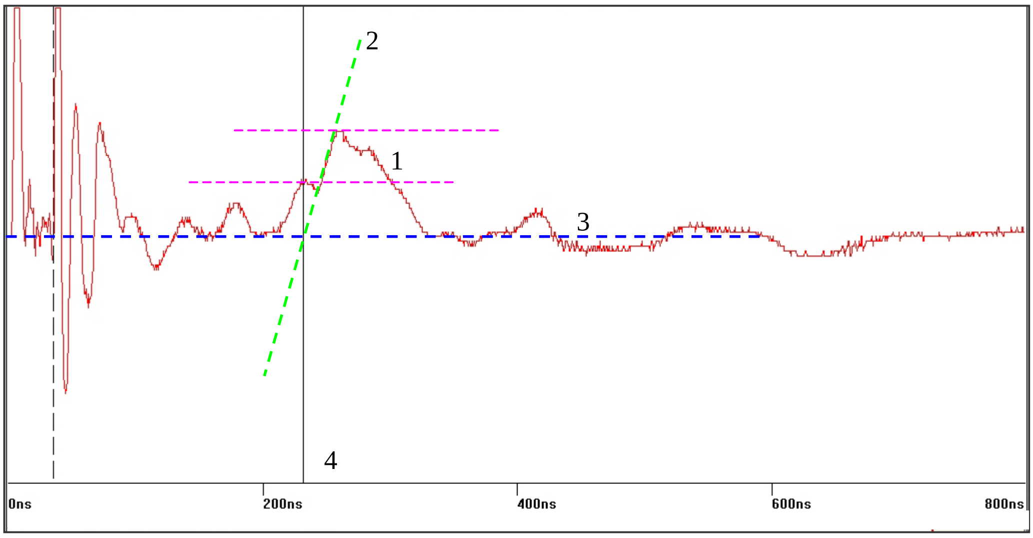
(b) <u>Example 2</u>

The first peak of the reflected pulse is less than 50% of the other peaks of the reflected pulse

(1) Identify the largest peak of the reflected pulse
(2) Extend the left sloping side of the largest peak of the reflected pulse
(3) Extend the leveled tail part of the waveform
(4) Take the time of travel as the interception point of (2) and (3)



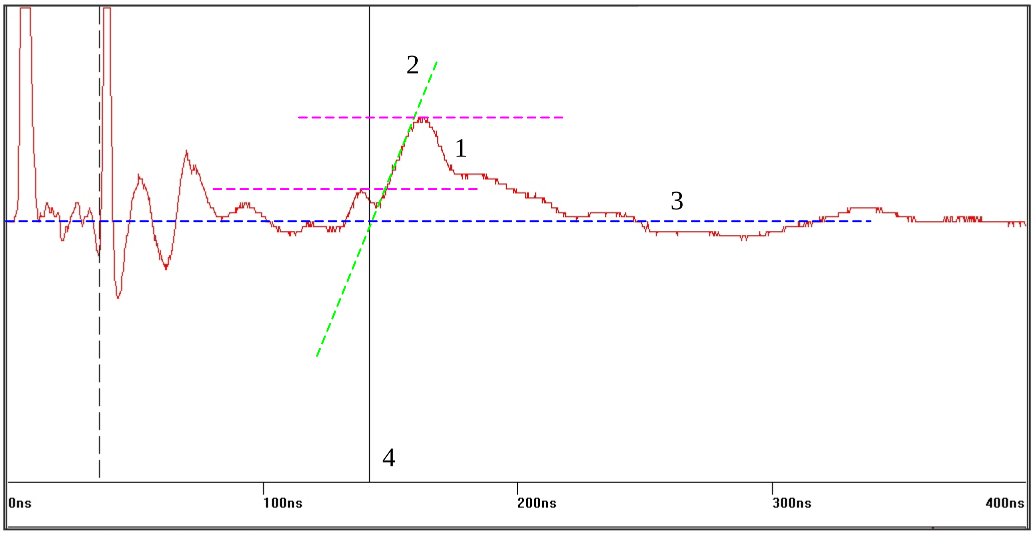


Figure A5 - Procedures to Identify the Rise of the Reflected Pulse with Multiple Peaks (Cont'd)

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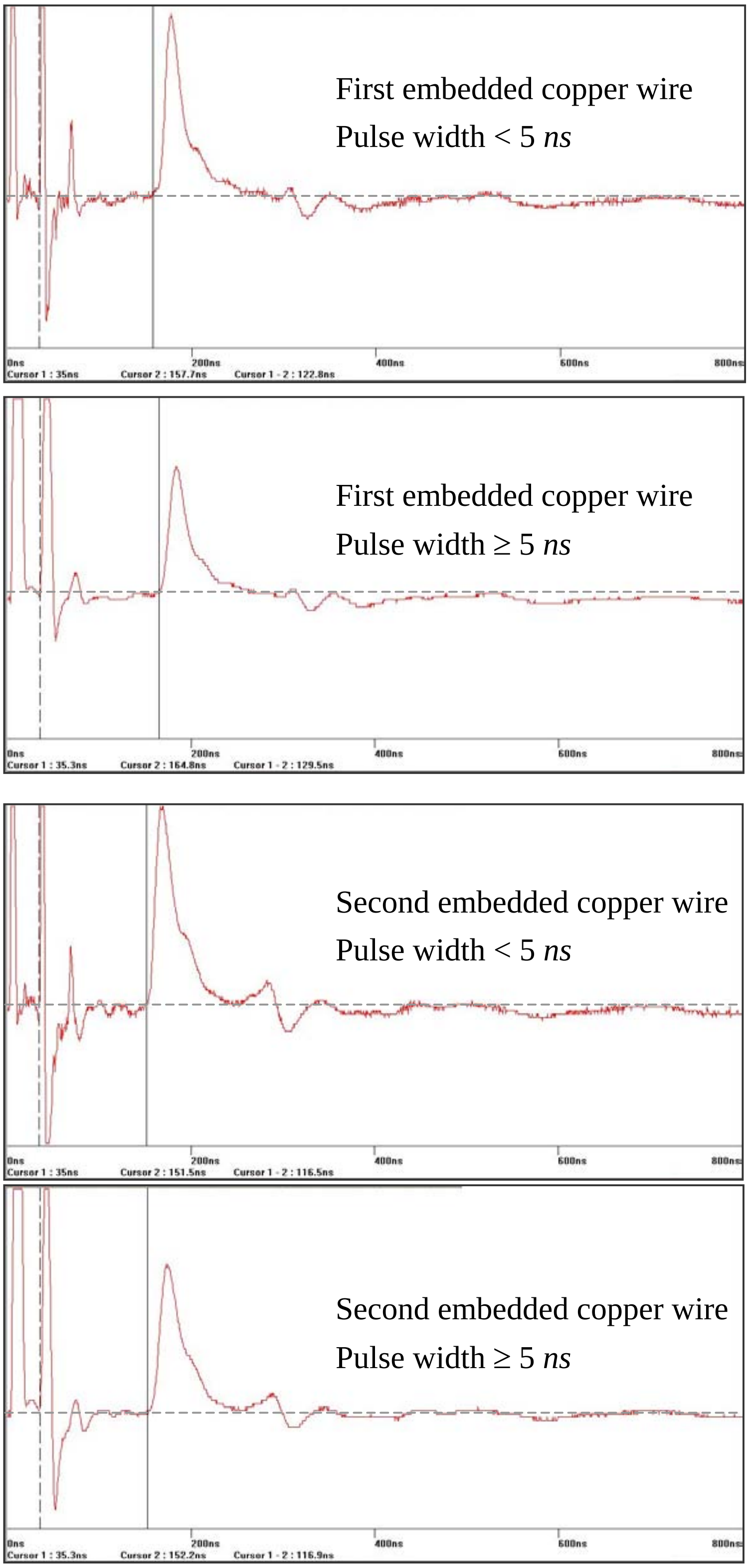

$$t_{c1} = \frac{122.8 + 129.5}{2} = 126.2\ ns$$

$$t_{c2} = \frac{116.5 + 116.9}{2} = 116.7\ ns$$

$$t_c = \frac{t_{c1} + t_{c2}}{2} = \frac{126.2 + 116.7}{2} = 121.5\ ns$$

Figure A6 - Determination of the Pulse Propagation Velocity from a Calibration Soil Nail

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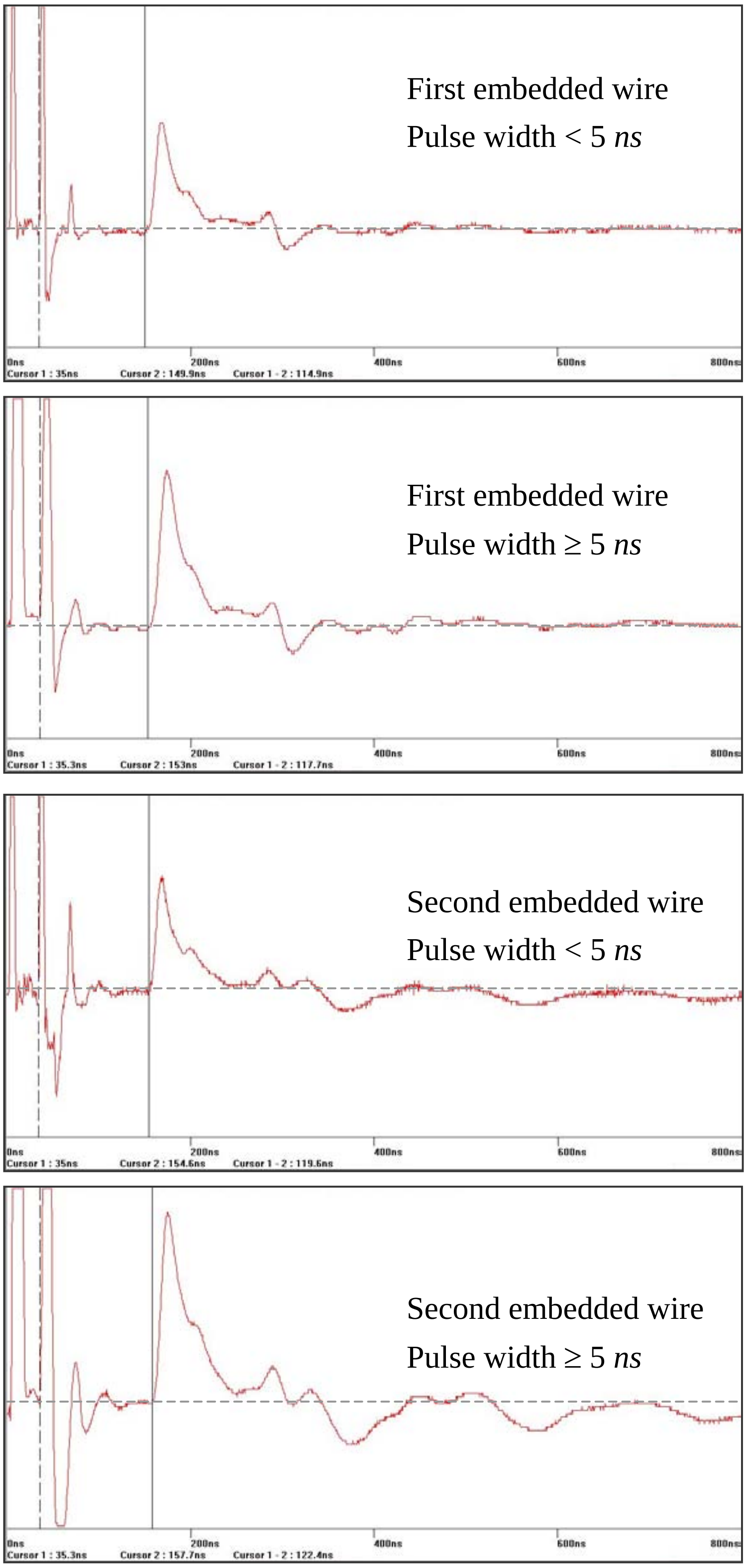

$$t_1 = \frac{114.9 + 117.7}{2} = 116.3\,ns$$

$$t_2 = \frac{119.6 + 122.4}{2} = 121.0\,ns$$

$$t = \frac{t_1 + t_2}{2} = \frac{116.3 + 121.0}{2} = 118.7\,ns$$

Figure A7 - Result of a Test Soil Nail

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APPENDIX B

EFFECT OF NAIL-UNRELATED UNCERTAINTY ON TDR-DEDUCED LENGTH

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Effect of Nail-unrelated Uncertainty on TDR-deduced Length

Notation

V_p: Calibrated pulse propagation velocity

L_d: Length of calibration soil nail

t_c: Measured pulse propagation time of the calibration soil nail

t_m: Measured pulse propagation time of the test soil nail

L_m: Deduced length of the test soil nail

$$V_p = \frac{L_d}{t_c}$$

$$L_m = V_p\, t_m = L_d\, \frac{t_m}{t_c}$$

The variability of the TDR-deduced length, L_m, due to the variability of t_m and t_c can be determined using first-order-second-moment (FOSM) method. The variance of the deduced length can be expressed as below:

$$\mathrm{Var}[\,L_m\,] = \left[\frac{\partial L_m}{\partial t_m}\right]_\mu^2 \mathrm{Var}[t_m] + \left[\frac{\partial L_m}{\partial t_c}\right]_\mu^2 \mathrm{Var}[t_c]$$

$$= \left[\frac{L_d}{t_c}\right]_\mu^2 \mathrm{Var}[t_m] + \left[\frac{L_d\, t_m}{t_c^2}\right]_\mu^2 \mathrm{Var}[t_c]$$

where Var[•] = variance of the random variable •

[•]$_\mu$ = the mean value of the random variable •

Since the expected value of L_m is

$$\mathrm{E}[L_m] = L_d \left[\frac{t_m}{t_c}\right]_\mu$$

The coefficient of variation, *c.o.v.*, of the deduced length becomes:

$$\{\mathrm{COV}[L_m]\}^2 = \frac{\mathrm{Var}[L_m]}{\{\mathrm{E}[L_m]\}^2}$$

$$= \left[\frac{1}{t_m}\right]_\mu^2 \mathrm{Var}[t_m] + \left[\frac{1}{t_c}\right]_\mu^2 \mathrm{Var}[t_c]$$

$$= \{\mathrm{COV}[t_m]\}^2 + \{\mathrm{COV}[t_c]\}^2$$

Assume the variability of $t_m = t_c$, which is due to equipment and multi-operator uncertainty as far as the test is concerned. And if the nail-unrelated uncertainty for Type 1 grout pipe, Type 2 grout pipe and conventional wire are 1.6%, 1.1% and 4.2% respectively. The corresponding *c.o.v*. on the deduced length are estimated to be 2.3%, 1.6% and 5.9% respectively.

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