USE OF TIME DOMAIN REFLECTOMETRY TO DETERMINE THE LENGTH OF STEEL SOIL NAILS WITH PRE-INSTALLED WIRES

GEO REPORT No. 198

W.M. Cheung

GEOTECHNICAL ENGINEERING OFFICE

CIVIL ENGINEERING AND DEVELOPMENT DEPARTMENT

THE GOVERNMENT OF THE HONG KONG SPECIAL ADMINISTRATIVE REGION

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Table of Contents

Table of Contents

Table of Contents

Table of Contents

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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R.K.S. Chan
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December 2006

Table of Contents
Table of Contents
Table of Contents
Table of Contents

FOREWORD

This report presents an update on the experience gained on the use of time domain reflectometry technique to determine soil nail length. The work strengthens the use of this technique in the quality control of soil nailing works in particular the checking of nail length.

This study was carried out by Dr W.M. Cheung of the Standards and Testing Division under the supervision of Dr D.O.K. Lo. Much of the data collection and analyses were performed by the technical staff, Mr. K.Y. Wong, Mr. K.C. Chan and Mr. P.C. Cheung. Valuable assistance was provided by the Public Works Central Laboratory, and Landslip Preventive Measures Divisions 1, 2 and 3. A number of colleagues and practitioners, in particular Dr Kelvin Yau of the City University of Hong Kong, gave useful comments on the statistical analyses and suggestions for improvement. All contributions are gratefully acknowledged.

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Table of Contents
Table of Contents
Table of Contents
Table of Contents

ABSTRACT

Since time domain reflectometry (TDR) has been identified as one of the potential non-destructive methods for quality control of soil nailing works in 2003, further development work has been carried out. This report updates on the experience gained on the use of this technique to determine soil nail length.

Various sources of uncertainty of a TDR test have been studied. They include human judgement in the carrying out of the test and interpretation of results, built-in error of the testing instrument, wire type, reinforcement size, and characteristics of grout sleeves. Among the sources of uncertainty, those related to human judgement and built-in error of testing instrument constitute the error directly in relation to the test. It is found that this test-related error is bounded by ±5% at 95% confidence level. Other major contributors of test-unrelated uncertainty include wire type and grout characteristics. In order to minimise the possible uncertainty of a TDR test, the installation details of the wire alongside a steel reinforcement has been standardized. Guidelines on testing procedure and interpretation of TDR test results are also given.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

CONTENTS

Table of Contents
Table of Contents
Table of Contents

Page No.

1. INTRODUCTION

Time Domain Reflectometry (TDR) is a well-established technique in electrical engineering for detection of faults in transmission lines. The use of this technique has been extended to geotechnical engineering for detection of slip planes in slope, groundwater level as well as for determination of soil moisture content (O'Connor & Dowding, 1999; Siddiqui et al, 2000). In principle, the technique involves sending an electrical pulse along a transmission line, which is in the form of coaxial or twin-conductor configuration, and receiving reflections or echoes induced by any mismatches/discontinuities in the line (Liu et al, 2002; Chajes et al, 2003).

TDR has been identified as one of the potential non-destructive methods for determining the length of installed steel soil nails by pre-installing a wire alongside a soil nail reinforcement (Cheung, 2003). The configuration is considered to be analogous to a twin-conductor transmission line. Since then, an extensive programme of using commercially available TDR cable fault detectors to determine the length of steel soil nails with pre-installed wires has been carried out. By August 2004, about 700 TDR tests have been conducted. This report updates on the experience gained on the use of this technique to determine soil nail length.

2. INSTALLATION DETAILS

Details of pre-installing a wire alongside a steel reinforcement during nail installation are shown in Figure 1. By connecting a TDR instrument to the steel reinforcement and the wire, the length of the soil nail can be determined. Under some circumstances, measurement can be taken after the casting of nail head if the contact of steel reinforcement is extended beyond the nail head via another piece of wire as shown in Figure 2. For the latter arrangement, it is important to ensure that there is good electrical connection between the steel reinforcement and the extension wire because field measurements indicate that where the electrical connection between the steel reinforcement and the extension wire is not good, this could result in erratic waveforms or even failure to receive any reflected signal from the nail end. Moreover, the extra time for a pulse travelling in the extended wire should be accounted for in the determination of nail length.

3. TESTING PROCEDURE AND INTERPRETATION OF TEST RESULTS

Guidelines on testing procedure and interpretation of TDR test results are given in Appendix A. The guidelines can also be downloaded from the CEDD website <www.cedd.gov.hk/eng/publications/manuals/manu_utdr.htm>. The test basically comprises two parts, viz. calibration of pulse propagation velocity from a nail of known length and measurement of the time for a pulse to propagate from the nail reinforcement head to its end. The purpose of calibration is to determine the pulse propagation velocity which can be used to determine the length of test nails at the same site of the same grout mix and same type of pre-installed wire. In general, at least one soil nail of known length should be selected for calibration. This nail can be of any bar size. It should preferably be the longest one among the test nails because for a given testing instrument, the resolution on the interpreted travel time of a pulse along a long nail is comparatively higher than that for a short one.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

4. UNCERTAINTY OF SOIL NAIL LENGTH ESTIMATION USING TDR TEST

4.1 General

The two key parameters that have to be known for the estimation of nail length are (i) the interpreted time for a pulse to travel from the nail reinforcement head to its end, t, and (ii) the pulse propagation velocity, v_p, calibrated from a nail (or nails) of known length (or lengths). This suggests that any factors that affect these two parameters will introduce uncertainty to the estimated nail length. Since the pulse propagation velocity is deduced from the interpreted travel time of a pulse, the uncertainty arising from the latter source will also affect the former source. Figure 3 shows the division of different sources of uncertainty of a TDR test.

4.2 Built-in Error of Testing Instrument

Even for a controlled testing medium, such as a transmission line, there is built-in error of the testing instrument. The magnitude of this testing error depends on the type of instrument. According to the instrument specifications, the error is generally less than 1%. The TDR cable fault detectors that were used in the present study have a built-in error less than 0.5%. This contributes negligible uncertainty to the determination of nail length.

4.3 Human Judgement

In practice, the major factor that affects the interpreted travel time of a pulse is the variation of human judgement in defining the point of reflection from the nail end in a TDR waveform. The reason is that the so-called step pulse generated by a TDR cable fault detector is indeed a smooth rising reflection from a nail end instead of a sharp step reflection, and sometimes this may obscure the identification of the point of initial arrival of the reflected signal. This phenomenon is commonly known as wave dispersion (Reynolds, 1997). In order to ensure the consistency of a test, it is a common practice in electrical engineering that the travel time be determined from between the points of initial rise of the generated and reflected pulses.

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.

4.3.1 Single-operator Uncertainty

The study of single-operator uncertainty involves the "repeatability" of a test where an operator follows the same procedure and carries out the same test on the same test item (BSI, 1994a). One reason for the variability of test results is that people are naturally variable even though the same item is tested by the same person following the same procedure. In the present case, three operators were selected randomly to perform TDR test and identify the reflection from the reinforcement end following the same testing procedure on six nails. Each operator took 10 measurements on each of the six nails. The length of the test nails varies from 5 m to 20 m. The test results in terms of interpreted pulse travel time are summarized in Table 1. The standard deviation and the corresponding coefficient of variation, *c.o.v.*, (i.e. standard deviation/mean of the ten measurements) for measurements

Table of Contents
Table of Contents
Table of Contents
Table of Contents

taken by Operator A vary from 0.34 to 2.51 nano-second (*n*s) and from 0.1% to 1.7%, respectively. Those for operators B and C are 0.99 to 3.73 *ns* and 0.7% to 1.2%, and 1.89 to 5.45 *ns* and 0.9% to 2.9%, respectively. In order to measure the variability in relation to the mean, the coefficient of variation will be adopted throughout the report. Note that among the measurements taken by each operator, the ones with comparatively higher variability (i.e. higher *c.o.v.*) in general correspond to those taken from nails of relatively shorter length. This substantiates the choice of the longest nail among the test nails for calibration test as recommended in Section 3 because for a given testing instrument, the resolution on the interpreted travel time of a pulse along a long nail is comparatively higher than that for a short one.

Although the operators are selected randomly, it would be necessary to test if the data obtained by different operators have similar characteristics before they are lumped together to estimate the single-operator uncertainty. In this regard, a *F*-statistic in one of the statistical methods under the heading 'Analysis of Variance' (ANOVA) (Paradine & Rivett, 1960) is employed to test the null hypothesis, which is in the present case defined as "no difference between the data obtained by the three operators". The *F*-statistic is a ratio of the mean square of data between operators to the mean square of data within operators. If the data obtained by different operators have significantly different characteristics, the *F*-statistic will be greater than a critical value for a designated significance level (usually taken as 5%). In this case, the critical value at 5% significance level is about 9.5 and the *F*-statistic is calculated to be 0.56. Hence the null hypothesis is not rejected, and the data obtained by the three operators are assumed to have similar characteristics.

Even though the data obtained by the three operators have similar characteristics, it would be necessary to test if the data obtained by individual operators contain statistical outliers. A statistical outlier is a point in a sample widely separated from the main cluster of points in the sample, and it should be disregarded in estimating the statistical properties of a sample. One may employ standard statistical tests such as Grubb's test (BSI, 1994b) to check the presence of outliers in a sample. In this case, the test performed by Operator C on nail No. 6 is classified as a statistical outlier by Grubb's test and is excluded from the sample. As a result, 17 values of *c.o.v.* have been used to estimate the single-operator uncertainty. The *c.o.v.* can be modelled as a random variable, and the mean and standard deviation are 0.9% and 0.43%, respectively. Furthermore, the data set is observed to fit a normal distribution. The validity of the assumed probabilistic model is checked by standard statistical tests such as Kolmogorov-Smirnov goodness-of-fit test (Ang & Tang, 1975), and is not rejected at the 5% significance level. If a normal distribution model is used, there is a 95% confidence level that the *c.o.v.* will not exceed 1.6%[1]. Strictly speaking, this uncertainty has also included the built-in error of the testing instrument as described in Section 4.2. Thus the 95% confidence level that the variability in the interpreted travel time of a pulse falls within $\pm 1.6\%$ from its mean value includes both the single-operator uncertainty and the built-in error of the testing instrument. If the single-operator uncertainty and the built-in error of the testing instrument are assumed to be independent, and that the latter value is 0.5%, one can estimate the single-operator uncertainty using the following equation (Ang & Tang, 1975):

[1] For a standard variate of mean, μ, and standard deviation, σ, there is a 95% confidence level that an estimate will not exceed $\mu+1.64\sigma$ in a one-tailed test.

Table of Contents Table of Contents Table of Contents Table of Contents

$$\left[\begin{array}{c}\text{Single-operator}\\ \text{uncertainty}\end{array} \right]^2 = \left[\begin{array}{c}\text{Uncertainty due to single}\\ \text{operator and instrument}\end{array} \right]^2 - \left[\begin{array}{c}\text{Uncertainty due to}\\ \text{instrument}\end{array} \right]^2 \quad \text{..........(1)}$$

In this case, the 95% confidence level that the variability in the interpreted travel time of a pulse due to single-operator uncertainty falls within ± 1.5% from its mean value.

4.3.2 Multi-operator Uncertainty

The variability of test results performed by different operators is usually greater than that performed by a single operator. Four operators were selected randomly to perform TDR tests and identify the reflection from the reinforcement end following the same testing procedure on 49 nails. Each operator conducted one test on each of the 49 nails. The variability of test results is related to the "reproducibility" of a test where different operators follow the same procedure and carry out the same test on the same test item (BSI, 1994a). Table 2 summarises the test results. The *c.o.v.* ranges from 0.5% to 8.9%. According to BSI (1994b), the test on nail No. C17 is classified as a statistical outlier using Grubb's test and is excluded from the sample. As a result, 48 values of *c.o.v.* have been used to estimate the multi-operator uncertainty. The mean and standard deviation of the *c.o.v.* are 2.2% and 1.5%, respectively. Similar to the data set in single-operator uncertainty, the data are observed to fit a normal distribution. The Kolmogorov-Smirnov goodness-of-fit test for the assumed normal distribution is not rejected at the 5% significance level. If a normal distribution model is used, there is a 95% confidence level that the *c.o.v.* will not exceed 4.7%. Thus there is a 95% confidence level that the variability in the interpreted travel time of a pulse due to multi-operator uncertainty and built-in error of the testing instrument falls within ± 4.7% from its mean value. If the multi-operator uncertainty and the built-in error of the testing instrument are assumed to be independent with the latter value being 0.5%, the multi-operator uncertainty is estimated to be 4.67% (say, 4.7%) using Equation (1).

4.4 Uncertainty Related to Wire Type

In order to investigate the effect of wire type on the pulse propagation velocity (or the interpreted pulse travel time), the corresponding velocities along a 10 m long reinforcement associated with different types of wire were determined under laboratory condition. In this case, no grout sleeve was involved and a total of eight wire types were tested. The main differences between the wire types are the wire diameter and the plastic sheath. The results are summarised in Table 3. The pulse propagation velocities vary from 0.192 m/*ns* to 0.252 m/*ns* with a *c.o.v*. of 8.1%.

Apart from the laboratory tests, field data were collected by an operator from four test nails at a site. Two types of wire were installed at each of the four test nails. While the diameters of the copper wires are the same, the properties of insulating plastic sheaths of the wires are different. Table 4 summarises the difference in the pulse propagation velocity along a nail associated with the two different types of wire. The percentage difference in the pulse propagation velocity due to these two types of wire varies from 8% to 17%. Note that the percentage difference in lieu of *c.o.v* in pulse propagation velocity has been used for comparison because the amount of data is not adequate to establish reliably the corresponding *c.o.v*. (data on only two types of wires for each nail are available). Nonetheless, the effect of uncertainties other than that from wire type, such as human judgement, quality of grout,

Table of Contents
Table of Contents
Table of Contents
Table of Contents

reinforcement length and diameter, have been minimized because the comparison of pulse propagation velocity is made from measurements on the same nail with different wire types by a single operator.

4.5 Uncertainty Related to Grout Sleeves

4.5.1 Uncertainty Related to Age of Grout

In order to investigate the possible effect of grout age on nail length estimation, the pulse propagation velocities were determined from a nail immediately and 5 days after the completion of grouting. The results are shown in Figure 4. It appears that the TDR waveform recorded on day 5 was more steady than that recorded immediately after the completion of grouting, which manifested a number of small reflections before the major reflection was reached. Moreover the pulse propagation velocity along the soil nail on day 5 was about 12% higher than that obtained immediately after the completion of grouting.

Apart from the above test, the pulse propagation velocities were determined by an operator on four nails of known lengths on 1 day, 2 days, 3 days, 4 days, 6 days and 7 days after completion of grouting. Similar measurements were taken at another site on a nail of known length immediately, 1 day, 2 days, 3 days, 5 days, 6 days and 7 days after completion of grouting. The results are shown in Table 5. For the former tests, the *c.o.v.* varies from 0.9% to 1.7%, whilst the *c.o.v.* for the latter test is 0.8% if the pulse propagation velocity determined immediately after grouting is excluded from the data set. However, if the pulse propagation velocity determined immediately after grouting in the latter test is included, the *c.o.v.* becomes 3.6%. Since the 95% confidence level that the uncertainty related to single-operator and built-in error of testing instrument is 1.6%, it appears that the age of grout has no significant effect on the test results after 1 day from grouting. If all the test results are plotted against the age of grout as in Figure 5, one can observe that the pulse propagation velocities become relatively steady 1 day after grouting.

Measurements were also taken at another site on three soil nails of known lengths on 7 days, 42 days and 128 days after completion of grouting. The results are shown in Table 6. The *c.o.v.* of the pulse propagation velocity varies from 0.4% to 1.6% with a mean of 1% (standard deviation is not calculated because only three data are available). This set of data comprising measurements for a considerably longer period after grouting further indicates that the age of grout has no significant effect on the test results.

4.5.2 Uncertainty Related to Grout Characteristics

The estimated length of a test nail is based on the pulse propagation velocity determined from a calibration nail. This implicitly assumes that the characteristics of grout sleeves between the calibration nail and the test nails are similar. However, if the characteristics of the grout sleeve of the test nails are different from those of the calibration nail, uncertainty will be induced. For example, if the grout sleeve of a test nail contains intermittent void sections, while that of the calibration is perfectly free of void, the actual pulse propagation velocity in the test nail will be higher than the calibration velocity. It is because the actual pulse propagation velocity in the test nail is the resultant velocity of those along the sections of air void and grout sleeve, and velocity in the former medium is higher than that in the latter. Indeed, if the grout characteristics of a calibration nail is substantially

Table of Contents
Table of Contents
Table of Contents
Table of Contents

different from those of test nails, one would obtain the estimated lengths of test nails either consistently longer or shorter than the design lengths. In this case, calibration should be carried out on additional nails of known lengths. No specific measurements have been carried out to quantify the uncertainties related to grout characteristics alone. Nevertheless, this is reflected in the overall uncertainty (see Section 4.7).

4.6 Uncertainty Related to Reinforcement

4.6.1 Uncertainty Related to Reinforcement Diameter

Four sets of pulse propagation velocities were determined from a sample of 114 reinforcement of diameters 25 mm, 32 mm, and 40 mm, coupled with two types of wire at two different sites. Test nails of similar lengths were selected for study in order to minimize possible effect of reinforcement length, if any, on the pulse propagation velocity. The tests were carried out by three operators and the results are shown in Table 7. The mean and standard deviation of the pulse propagation velocity for reinforcement of diameters 25 mm and 32 mm at site A are 0.080 m/*ns* and 0.0028 m/*ns* (*c.o.v.* = 3.5%), and 0.079 m/*ns* and 0.0024 m/*ns* (*c.o.v.* = 3.1%), respectively. Those for reinforcement of diameters 32 mm and 40 mm at site B are 0.081 m/*ns* and 0.0020 m/*ns* (*c.o.v.* = 2.4%), and 0.082 m/*ns* and 0.0021 m/*ns* (*c.o.v.* = 2.5%), respectively. Note that the variability of the pulse propagation velocity for each reinforcement diameter (i.e. *c.o.v.* ranges from 2.4% to 3.5%) is less than the 95% confidence level of the multi-operator uncertainty (i.e. 4.7%) as determined from Section 4.3.2.

The results in Table 7 indicate that for a given site with nails of similar length, the percentage difference between the mean pulse propagation velocities determined from different reinforcement diameters is in the order of 1%. It suggests that the reinforcement diameters commonly used in soil nailing have no significant effect on the pulse propagation velocity. The mean pulse propagation velocity of a large number of nails at a site has been used for comparison in order to minimise effects due to variation between soil nails (e.g. characteristics of grout) other than the reinforcement diameter. Moreover, the percentage difference in mean pulse propagation velocity has been used because the amount of data is not adequate to establish the corresponding *c.o.v.* (only two reinforcement sizes at each site were available).

4.6.2 Uncertainty Related to Reinforcement Length

Five sets of pulse propagation velocities were determined by three operators from a sample of 202 reinforcement bars of lengths 8 m, 10 m, 12 m, 13 m, and 14 m. They all have the same type of wire and were installed at the same site. The results in Table 8 indicate that the *c.o.v.* of the calibrated pulse propagation velocity for each group of reinforcement length varies from 2.2% to 5.2%. ANOVA is employed to test the null hypothesis, which is defined in the case as "no difference between the pulse propagation velocities obtained from nails of different lengths". The *F*-statistic is calculated to be 0.3, which is less than the critical value at 5% significance level of 2.4. In other words, the null hypothesis is not rejected, and there is no obvious evidence showing any correlation between the variability of the pulse propagation velocity and reinforcement length. This suggests that reinforcement length has insignificant effect on the test results.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

It is noted that the variability of the pulse propagation velocity for the group of 8 m long nails (*c.o.v.* = 5.2%) is highest among the nail groups. Although the human error in identifying the reflection for a short nail is comparatively larger than that for a long one, the relatively higher variability of propagation velocity in this nail group, which is greater than the 95% confidence level of the multi-operator uncertainty, could be due to reasons other than nail length such as a higher variability in grout characteristics among the nails in this group. It is because the establishment of the multi-operator uncertainty has already included nails of this range of length.

4.6.3 Presence of Reinforcement Connector (Coupler)

Although the presence of couplers may cause extra travel time of a pulse (each coupler may lengthen a nail bar by 10 mm to 20 mm), the corresponding uncertainty is relatively negligible.

4.7 Overall Uncertainty

In the preceding Sections, various sources of uncertainties in nail length estimation using TDR test have been considered. Among the different sources of uncertainty, some of them can be totally eliminated, while others can only be minimised. For example, the uncertainty related to the difference in wire type can be eliminated by using the same type of wire in the calibration and test nails. The uncertainty due to human judgement can only be reduced by providing a standard procedure for testing and guidelines on result interpretation. Similarly, the effect of variability of grout characteristics among nails can be reduced by calibrating the pulse propagation velocity from a nail installed on the same site as the test nails or to perform more calibration tests if the nail used for calibration is suspected to be unrepresentative. Nevertheless, irrespective of the sources of uncertainty, the maximum error bound can be estimated when the estimated lengths are compared with the as-built lengths of all the 700 test nails without making any distinction with respect to operators, reinforcement diameter and length, wire type, characteristics of grout, etc. These 700 test nails are spread over 9 different sites. The frequency distribution of the length difference is presented in Figure 6(a). Note that the number of measurements is greater than 700 because some of the nails were tested by four operators for the estimation of multi-operator uncertainty. The data set is observed to fit a normal distribution. The Kolmogorov-Smirnov goodness-of-fit test for the assumed normal distribution is not rejected at the 5% significance level. By fitting the probability distribution of the length difference with a normal model, as in Figure 6(b), the mean and standard deviation of the model are found to be 0.82% and 4.16%, respectively. 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 -7.3% and + 8.9% (i.e. 0.82% ± 1.96 x 4.16%) of the as-built length.

5. DISCUSSION AND CONCLUSION

Various sources of uncertainties in nail length estimation using the TDR test have been studied. They are classified as the nail-unrelated and nail-related sources. The former includes human judgement and built-in error of the testing instrument, which is not affected

Table of Contents
Table of Contents
Table of Contents
Table of Contents

by the natural variability in nail characteristics (e.g. reinforcement size, wire type, grout quality, etc), while the latter includes the natural variability in the nail characteristics and other unaccounted factors.

Recognizing the existence of these uncertainties, guidelines on testing procedure and interpretation of test results have been standarized so as to reduce the pertinent uncertainties as far as possible. The TDR cable fault detector that has been used in the present study has an error of less than 0.5%. Based on field measurements, the 95% confidence level of the single-operator and multi-operator uncertainties of 1.5% and 4.7% respectively indicate that the TDR test (viz. identification of reflection from soil nail end using the TDR instrument) is both repeatable and reproducible. Since these types of uncertainty are not affected by the natural variability in nail characteristics, it suggests that the 95% confidence level of the error bound of a TDR test, which is not related to the natural variability in nail characteristics, is about ±5%.

The variation in the pulse propagation velocity due to different types of wire can be as large as 17% underlines the importance of using the same wire type in the nail for calibration of pulse propagation velocity and the test nails. Similarly, fresh grout can have significantly different pulse propagation velocity, and TDR tests should be conducted at least 1 day after the completion of grouting. On the other hand, the uncertainty due to reinforcement size (both diameter and length), and the presence of couplers appears to be insignificant when compared with other sources of uncertainty.

The 95% confidence level of the overall error in length estimation is estimated to be between -7.3% and + 8.9%. This increase in the error bound with respect to those unrelated to nail characteristics reflects indirectly the possible variability in the characteristics of soil nails within a site and between the sites that have been installed to the current construction practice (e.g. the method of nail installation, grouting, etc).

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Table of Contents
Table of Contents
Table of Contents
Table of Contents

LIST OF TABLES

Table 1 - Single-operator Uncertainty of TDR Tests

Test Nail No.	1			2			3			4			5			6				
Operator	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C		
Interpreted Time of Travel (*ns*)[1]	453.9	453.4	453.9	340.2	339.7	344.1	244.1	241.7	246.1	232.4	229.9	234.3	106.9	100.5	106.9	134.3	120.1	126.5		
	453.4	442.2	453.9	339.7	332.4	344.1	245.6	242.2	242.2	231.9	226.5	230.4	112.3	101.0	104.9	133.8	120.6	120.6		
	453.9	446.1	446.1	336.3	336.3	336.3	242.2	242.2	242.2	232.4	230.4	226.5	106.9	101.0	102.9	134.3	120.6	120.6		
	454.2	450.3	453.9	336.5	336.5	340.2	246.3	238.5	242.2	234.6	226.7	230.4	107.1	103.2	105.9	135.5	120.8	124.5		
	453.9	449.0	450.0	336.3	335.3	340.2	246.1	241.2	238.2	232.4	225.5	226.5	106.9	100.0	102.9	136.3	119.6	118.6		
	453.9	450.0	453.9	336.3	338.0	336.3	242.0	242.0	242.2	232.0	226.0	226.5	106.0	102.0	102.9	134.0	120.0	116.7		
	453.8	445.8	442.2	333.8	333.8	336.3	243.8	241.8	238.2	233.8	225.8	226.5	106.8	101.8	106.9	133.8	121.8	116.7		
	453.8	453.8	442.2	333.8	333.8	340.2	243.8	241.8	242.2	233.8	225.8	226.5	106.8	101.8	102.9	134.8	117.8	116.7		
	453.5	445.0	453.9	333.5	333.0	340.2	243.5	237.0	242.2	233.5	229.0	226.5	106.5	101.0	106.9	134.5	117.0	120.6		
	453.0	450.0	442.2	333.0	333.0	336.3	243.0	237.0	242.2	233.0	229.0	226.5	106.0	100.0	102.9	134.0	120.0	116.7		
Mean (*ns*)	453.7	448.6	449.2	335.9	335.2	339.4	244.0	240.5	241.8	233.0	227.5	228.1	107.2	101.2	104.6	134.5	119.8	119.8		
Standard Deviation (*ns*)	0.34	3.73	5.45	2.51	2.41	3.08	1.52	2.16	2.25	0.91	1.90	2.73	1.83	0.99	1.89	0.81	1.43	3.48	Mean (%)	Standard Deviation (%)
Coefficient of Variation (*c.o.v.*) (%)	0.1	0.8	1.2	0.7	0.7	0.9	0.6	0.9	0.9	0.4	0.8	1.2	1.7	1.0	1.8	0.6	1.2	2.9	0.9[2]	0.43[2]

Notes:
(1) *ns* = nano-second (10^{-9}sec)
(2) Test results by Operator C on nail No. 6 have been disregarded. See Section 4.3.1 for details.
(3) Length of test nails ranges from 5 m to 20 m.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table 2 - Multi-operator Uncertainty of TDR Tests

Test Nail No.	Interpreted Time of Travel (*ns*)				Mean, μ (*ns*)	Standard Deviation, σ (*ns*)	Coefficient of Variation (σ/μ) (%)
	Operator A	Operator B	Operator C	Operator D			
R2-2	279.3	289.4	285.6	282.2	284.1	4.4	1.5
R2-3	268.6	276.6	270.7	270.0	271.5	3.5	1.3
R2-4	270.7	278.7	272.9	270.0	273.1	3.9	1.4
R2-5	270.7	276.6	272.9	270.0	272.6	3.0	1.1
R2-6	268.6	276.6	275.0	270.0	272.6	3.9	1.4
R2-7	283.5	289.4	283.5	280.6	284.3	3.7	1.3
R2-8	275.0	283.0	279.3	276.3	278.4	3.6	1.3
R2-9	268.6	276.6	272.9	270.0	272.0	3.5	1.3
R2-10	285.6	283.0	272.9	276.3	279.5	5.9	2.1
R3-5	230.3	238.3	223.9	233.8	231.6	6.1	2.6
R3-6	232.5	238.3	223.9	229.5	231.1	6.0	2.6
R3-7	243.1	246.8	226.1	240.2	239.1	9.0	3.8
R3-8	236.7	240.4	234.6	233.8	236.4	2.9	1.2
R3-9	236.7	238.3	219.7	231.7	231.6	8.4	3.6
R3-10	238.8	242.6	232.5	238.0	238.0	4.2	1.8
R5-1	183.5	183.0	177.1	178.5	180.5	3.2	1.8
R5-2	183.5	183.0	179.3	178.5	181.1	2.5	1.4
R5-3	175.0	176.6	170.7	170.0	173.1	3.2	1.9
R5-4	175.0	174.5	170.7	167.8	172.0	3.4	2.0
R5-5	183.5	180.9	179.3	176.3	180.0	3.0	1.7
R5-6	170.7	174.5	168.6	170.0	171.0	2.5	1.5
R5-7	179.3	180.9	170.7	174.0	176.2	4.7	2.7
R5-8	185.6	185.1	183.5	176.3	182.6	4.3	2.4
R5-9	192.0	187.2	185.6	178.5	185.8	5.6	3.0
R5-10	175.0	170.2	170.7	167.8	170.9	3.0	1.8
C1	299.5	292.6	300.0	305.0	299.3	5.1	1.7
C2	306.4	296.8	300.0	305.2	302.1	4.5	1.5
C3	300.0	296.8	291.5	302.9	297.8	4.9	1.6
C4	312.8	309.6	300.0	316.9	309.8	7.2	2.3
C5	291.5	279.8	295.7	293.9	290.2	7.2	2.5
C6	300.0	296.8	300.0	305.2	300.5	3.5	1.2
C7	300.0	296.8	300.0	300.1	299.2	1.6	0.5
C8	304.3	292.6	300.0	300.3	299.3	4.9	1.6
C9	308.5	309.6	304.3	292.7	303.8	7.7	2.5
C10	316.5	322.3	308.5	316.4	315.9	5.7	1.8
C11	318.6	326.6	304.3	291.2	310.2	15.7	5.0
C12	327.1	326.6	304.3	309.3	316.8	11.8	3.7
C13	337.8	343.6	304.3	300.9	321.7	22.2	6.9
C14	331.4	322.3	312.8	297.1	315.9	14.7	4.6
C15	384.6	373.4	380.9	381.9	380.2	4.8	1.3
C16	354.8	364.9	355.3	371.8	361.7	8.2	2.3
C17	363.3	377.7	317.0	391.0	362.3	32.2	8.9
E1	393.1	394.7	351.1	401.9	385.2	23.1	6.0
E2	410.1	403.2	410.6	408.0	408.0	3.4	0.8
E3	376.1	377.7	321.3	349.5	356.2	26.6	7.5
E4	418.6	416.0	410.6	415.0	415.1	3.3	0.8
E5	414.4	411.7	410.6	416.0	413.2	2.5	0.6
E6	397.3	394.7	397.9	401.9	398.0	3.0	0.7
E7	397.3	394.7	402.1	397.9	398.0	3.1	0.8
Mean (%)							2.2(2)
Standard Deviation (%)							1.5(2)

Notes:
(1) Each operator conducted one test on each of the 49 nails with length ranging from 8 m to 20 m.
(2) Test results on nail No. C17 have been disregarded. See Section 4.3.2 for details.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table 3 - Pulse Propagation Velocity for a 10 m Reinforcement Bar Coupled with Eight Types of Wire Measured under Laboratory Condition

Type of Wire	Pulse Propagation Velocity (m/*ns*)	*c.o.v.* (%)
W 1	0.252	
W 2	0.236	
W 3	0.234	
W 4	0.246	
W 5	0.220	
W 6	0.222	
W 7	0.192	
W 8	0.230	
Mean	0.230	8.1

Note: There was no grout sleeve around the reinforcement bar.

Table 4 - Effect of Wire Type on Pulse Propagation Velocity

Test Nail No.	Diameter of Reinforcement (mm)	Reinforcement Length (m)	Type of Wire	Pulse Propagation Velocity (m/*ns*)	Difference in Pulse Propagation Velocity (%)
T1	25	20	19	0.096	8
			20	0.089	
T2	25	15	19	0.103	16
			20	0.089	
T3	25	11	19	0.100	12
			20	0.091	
T4	25	10	19	0.103	17
			20	0.088	

Notes: (1) % Difference in pulse propagation velocity

$$= \frac{\text{Higher pulse propagation velocity (e.g. Wire Type 19)} - \text{Lower pulse propagation velocity (e.g. Wire Type 20)}}{\text{Lower pulse propagation velocity (e.g. Wire Type 20)}}$$

(2) Two types of wires have been installed at each of the four test nails.

Table of Contents

Table of Contents

Table of Contents

Table of Contents

Table 5 - Effect of Grout Age on Pulse Propagation Velocity within the First Seven Days after Completion of Grouting

Site	Test Nail No.	Pulse Propagation Velocity at Different Times after Completion of Grouting (m/*ns*)								*c.o.v*[(1)]. (%)
		Immediately after grouting	1 day	2 days	3 days	4 days	5 days	6 days	7 days	
1	R1	0.083	-	-	-	-	0.093	-	-	-
2	G1	-	0.085	0.088	0.085	0.085	-	0.086	0.085	1.2
	G2	-	0.084	0.085	0.085	0.085	-	0.083	0.083	1.0
	G3	-	0.085	0.084	0.084	0.084	-	0.085	0.083	0.9
	G4	-	0.082	0.085	0.085	0.085	-	0.085	0.085	1.7
3	TDR 1	0.072	0.079	0.078	0.079	-	0.079	0.079	0.079	0.8

Note: (1) Pulse propagation velocity immediately after grouting is excluded in the calculation of *c.o.v.*

Table 6 - Effect of Grout Age on Pulse Propagation Velocity beyond Seven Days after Completion of Grouting

Test Nail No.	Pulse Propagation Velocity Calibrated at Different Times after Completion of Grouting (m/*ns*)			*c.o.v.* (%)
	7 days	42 days	128 days	
1	0.097	0.096	0.097	0.4
2	0.102	0.103	0.105	1.6
3	0.103	0.104	0.102	1.1
Mean				1.0

Table 7 - Effect of Reinforcement Diameter on Pulse Propagation Velocity

Site	Diameter of Reinforcement (mm)	Reinforcement Length (m)	Type of Wire	No. of Test Nails	Mean Pulse Propagation Velocity (m/*ns*)	Standard Deviation (m/*ns*)	*c.o.v.* (%)	Difference in Mean Pulse Propagation Velocity (%)
A	25	13	1	43	0.080	0.0028	3.5	1
	32	13		42	0.079	0.0024	3.1	
B	32	15	2	15	0.081	0.0020	2.4	1
	40	12		14	0.082	0.0021	2.5	

Note:

$$\%\ \text{Difference in mean pulse propagation velocity} = \frac{\text{Higher mean pulse propagation velocity} - \text{Lower mean pulse propagation velocity}}{\text{Lower mean pulse propagation velocity}}$$

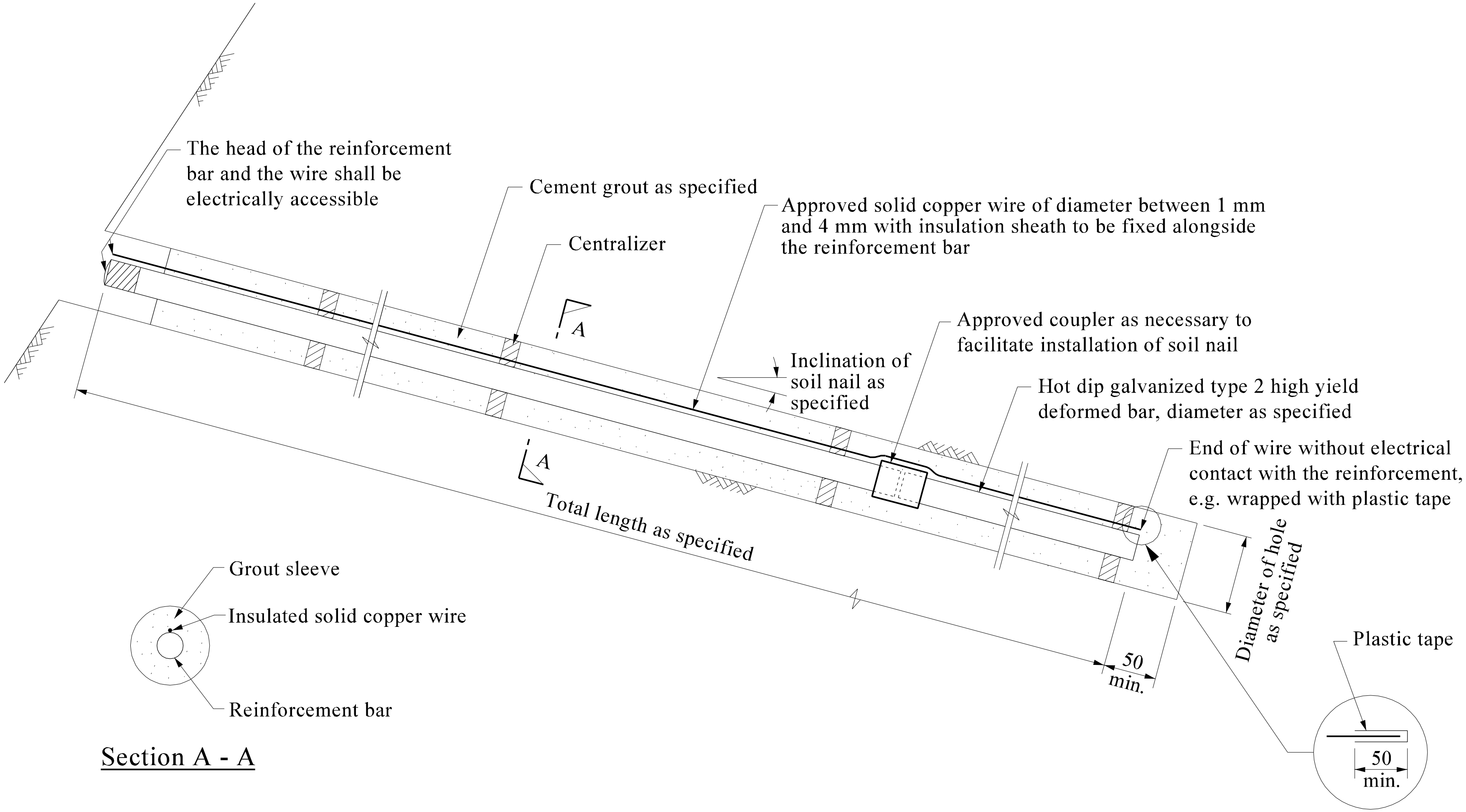
Table of Contents Table of Contents Table of Contents Table of Contents

Table 8 - Effect of Reinforcement Length on Pulse Propagation Velocity

Site	Diameter of Bar (mm)	Reinforcement Length (m)	No. of Test Nails	Type of Wire	Mean Pulse Propagation Velocity (m/*ns*)	Standard Deviation (m/*ns*)	*c.o.v.* (%)
A	25	8	19	1	0.084	0.0044	5.2
	25	10	67	1	0.078	0.0021	2.7
	25	12	34	1	0.078	0.0022	2.8
	25	13	43	1	0.080	0.0027	3.4
	25	14	39	1	0.079	0.0017	2.2

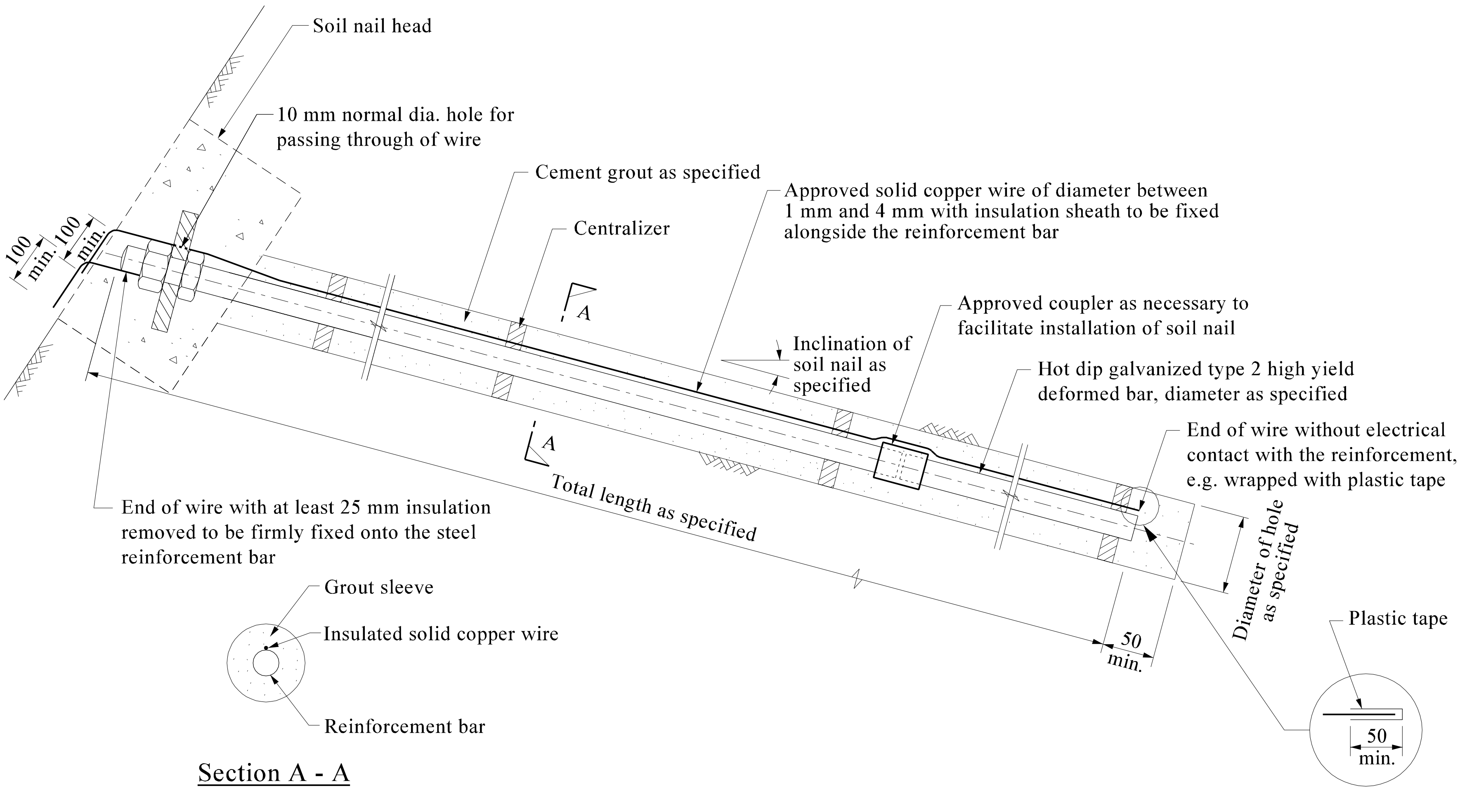
Table of Contents
Table of Contents
Table of Contents
Table of Contents

LIST OF FIGURES



Note: All dimensions are in millimetres.

Figure 1 - Details of Provision of a Wire for Determination of Soil Nail Reinforcement Length Using Time Domain Reflectometry



Note: All dimensions are in millimetres.

Figure 2 - Details of Provision of a Wire for Determination of Soil Nail Reinforcement Length Using Time Domain Reflectometry with Cast Nail Head

Table of Contents
Table of Contents
Table of Contents
Table of Contents

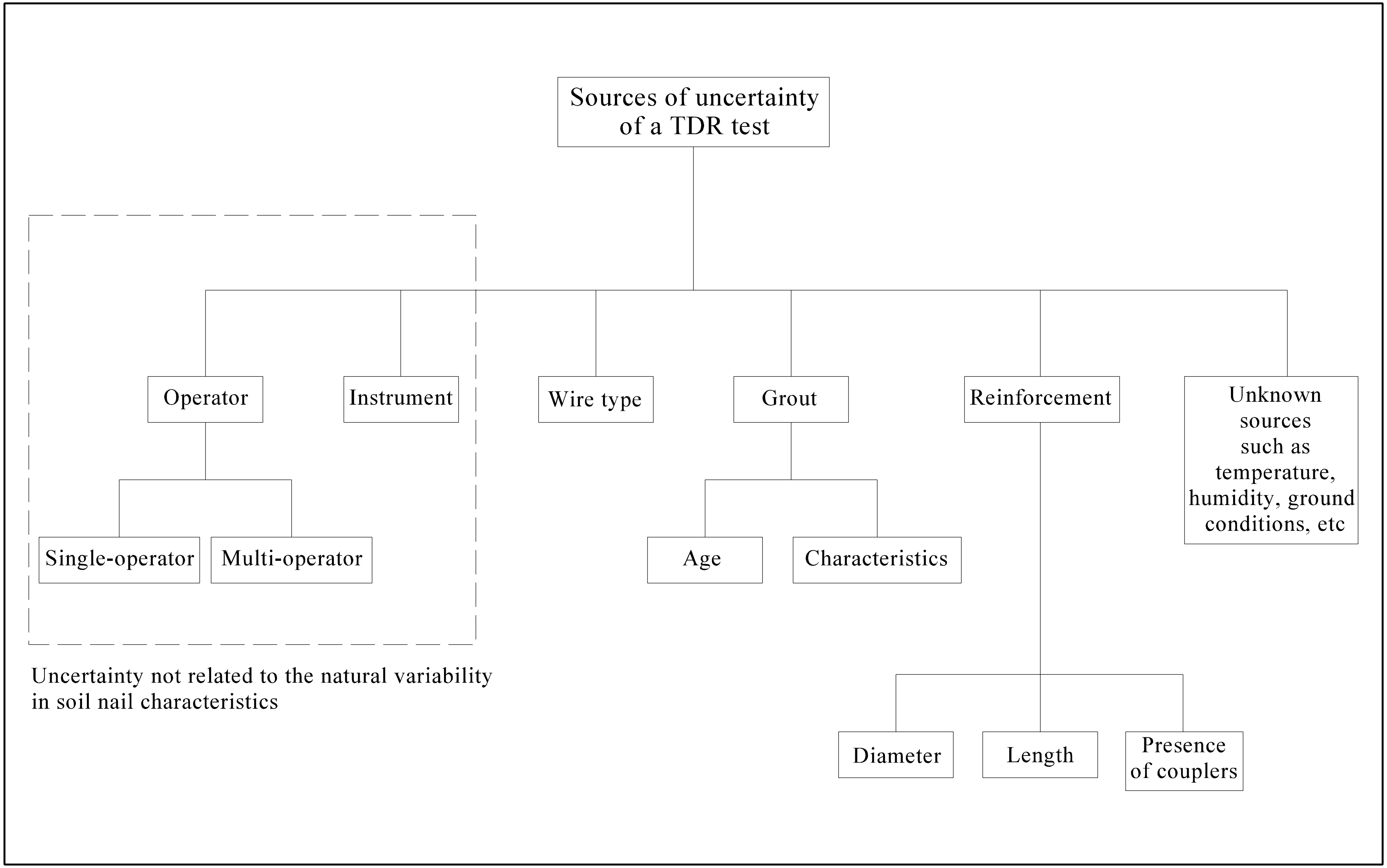
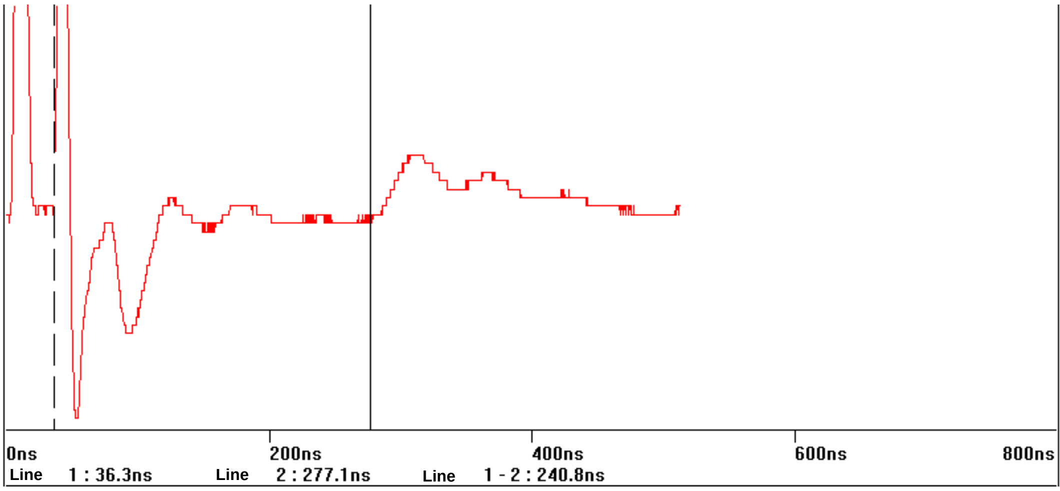


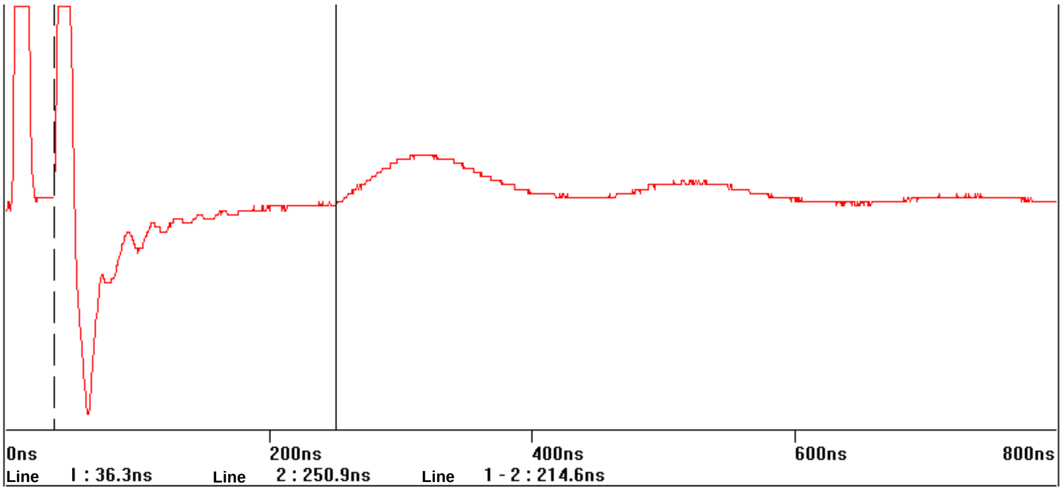
Figure 3 - Sources of Uncertainty of a TDR Test

v_p = 0.08306 m/*ns* (immediately after completion of grouting)



(a)

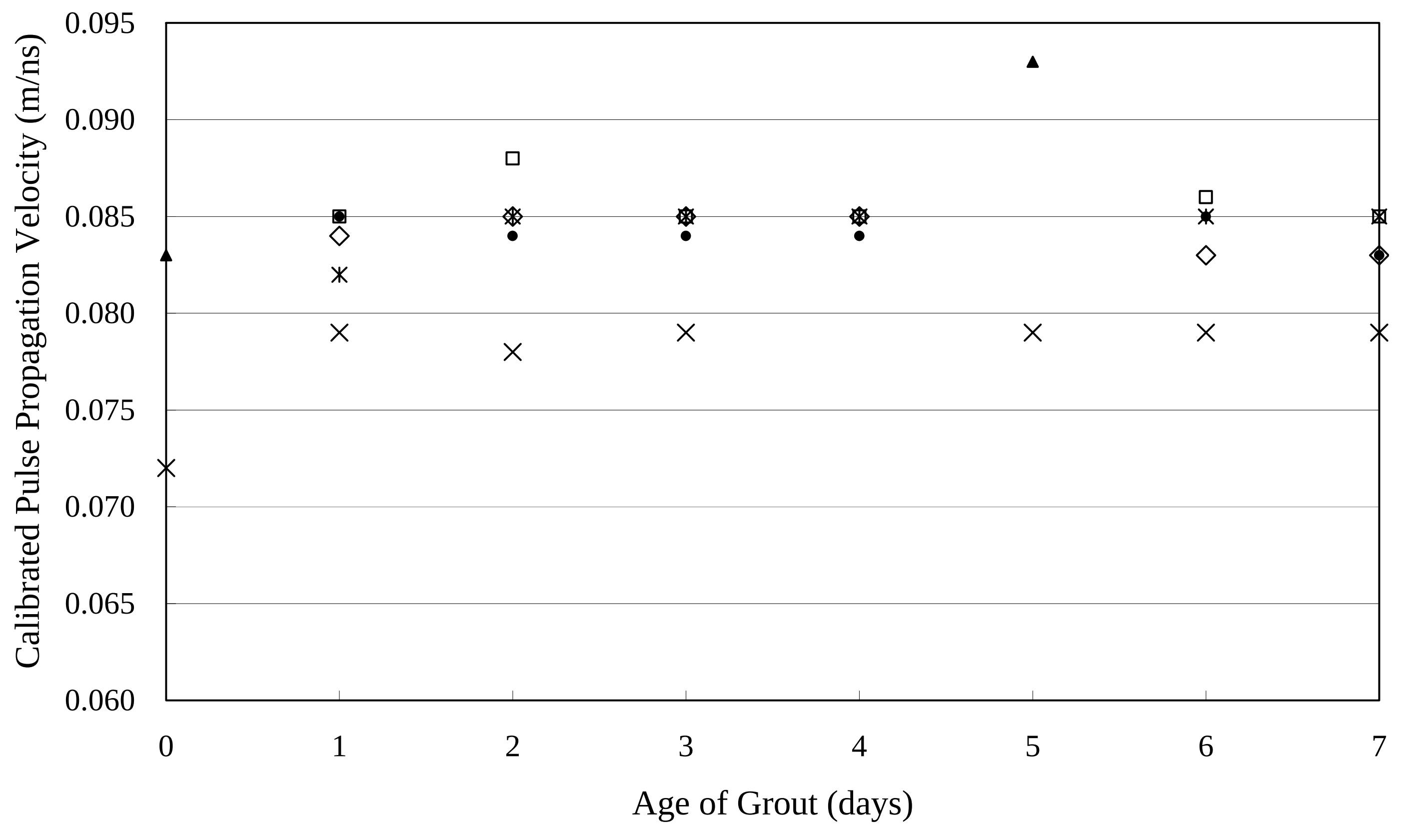
v_p = 0.09320 m/*ns* (5 days after completion of grouting)



(b)

Figure 4 - Effect of Grout Age on TDR Waveform

Table of Contents
Table of Contents
Table of Contents
Table of Contents



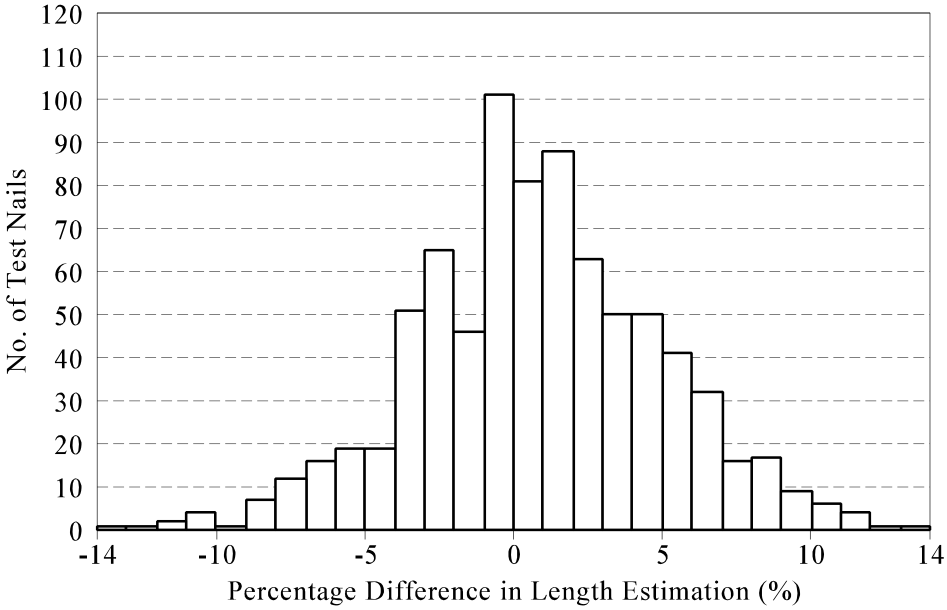
Legend:

▲ Site 1 □ ● ⋇ ◇ ○ Site 2 ╳ Site 3

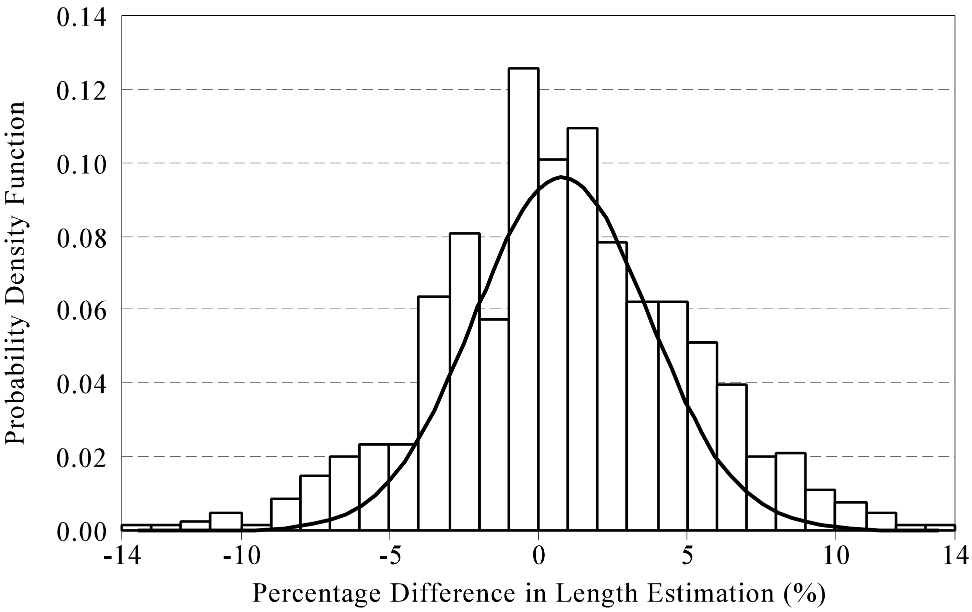
Note: Day 0 means immediately after grouting.

Figure 5 - Effect of Grout Age on Pulse Propagation Velocity

Table of Contents
Table of Contents
Table of Contents
Table of Contents



(a) Frequency Distribution of Estimation Error



(b) Probability Density Function of Estimation Error

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

Figure 6 - Overall Uncertainty in Soil Nail Length Estimation Using TDR Tests

Table of Contents
Table of Contents
Table of Contents
Table of Contents

APPENDIX A

USE OF TIME DOMAIN REFLECTOMETRY (TDR) TO DETERMINE THE LENGTH OF INSTALLED STEEL SOIL NAIL WITH A PRE-INSTALLED WIRE

Table of Contents
Table of Contents
Table of Contents
Table of Contents

1. Preparation

1.1 A wire shall be installed alongside the steel reinforcement with details shown in Figure A1.

1.2 No TDR test shall be carried out on a nail within 1 day after the completion of grouting.

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

2. Test Procedure and Interpretation of Test Results

Calibration

2.1 Select at least one soil nail of known length for determination of pulse propagation velocity. If soil nails of different lengths and different bar diameters are installed at a site, one of the longest nails of any bar diameter shall be selected for calibration purpose. The determined pulse propagation velocity can be applied to assess the length of other soil nails (different lengths and diameters) provided that the approved grout mix and type of pre-installed wire used are the same as that of the calibration nail. Otherwise separate calibration measurements shall be carried out for soil nails with different grout mixes or pre-installed wires.

2.2 With the clips of the test lead unconnected as in Figure A2(a), move line “1” on the 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” can be confirmed by connecting the clips. When the clips are connected, the polarity of the pulse situated at line “1” would be reversed as indicated in Figure A2(b).

2.3 Connect the clips to the calibration nail as shown in Figure A2(c); one to the steel reinforcement and the other to the pre-installed wire.

2.4 Identify the pulse reflected from the end of the test 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 A2(c)).

2.5 Record the time of travel between line “1” and line “2”, and the waveform.

2.6 Repeat steps (2.2) to (2.5) using different pulse widths. In principle, one should obtain the same result regardless of the pulse widths used . In practice, however, the number of small amplitude reflections and the degree of wave dispersion effect depend on the pulse width and the nail length. In some cases, this may obscure the identification of the pulse reflected from the nail end. It is suggested that measurements be taken with pulses of the following widths: less than 5 nano-second (*ns*), between 5 to 20 *ns*, and greater than 20 *ns*.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

2.7 Among the measurements taken with pulses of different widths, select those with a clear and distinct reflection for calculating the average value of time of travel, t_c.

2.8 Determine the average pulse propagation velocity using Equation (A1a).

$$v_1 = \frac{2L_c}{t_c} \tag{A1a}$$

where L_c is length of soil nail for calibration, t_c is the average time of travel between line "1" and line "2", which corresponds to the time of travel of the pulse from the nail head to the nail end and back to the nail head, i.e. 2 times the nail length.

Some TDR instruments make allowance for the travel time of the pulse and the t_c shown on the display panel actually corresponds to one nail length. In such cases, Equation (A1b) should be used to determine the average pulse propagation velocity. User should refer to the specification of their TDR instrument to check which equation is to be used.

$$v_2 = \frac{L_c}{t_c} \tag{A1b}$$

Measurement of Nail Lengths

2.9 Carry out steps (2.2) to (2.7) for each soil nail to be tested.

2.10 Estimate the length of each soil nail, *L*, using Equation (A2a) or (A2b) as appropriate.

$$L = \frac{v_1 t}{2} \tag{A2a}$$

or

$$L = v_2 t \tag{A2b}$$

where v_1 or v_2 is the average pulse propagation velocity determined from the calibration test, and *t* is the average time interval between line "1" and line "2" measured from the soil nail.

3. Worked Example

Calibration

A 15 m soil nail was selected for the determination of pulse propagation velocity. Measurements were taken with three different pulse widths, and the results are shown in Figure A3. The average pulse propagation velocity, v_1, is given by:

Table of Contents
Table of Contents
Table of Contents
Table of Contents

$$t_c = \frac{291.9 + 297.2 + 303.3}{3} = 297.5\,ns$$

$$v_1 = \frac{2 \text{ x } 15}{297.5} = 0.10084 \text{ m}/ns$$

Measurement

A nail of unknown length was tested using three different pulse widths. The results are shown in Figure A4. Based on the average pulse propagation velocity obtained from the calibration test, the length of the nail, *L*, is estimated to be:

$$t = \frac{216.9 + 220.7 + 230.2}{3} = 222.6\,ns$$

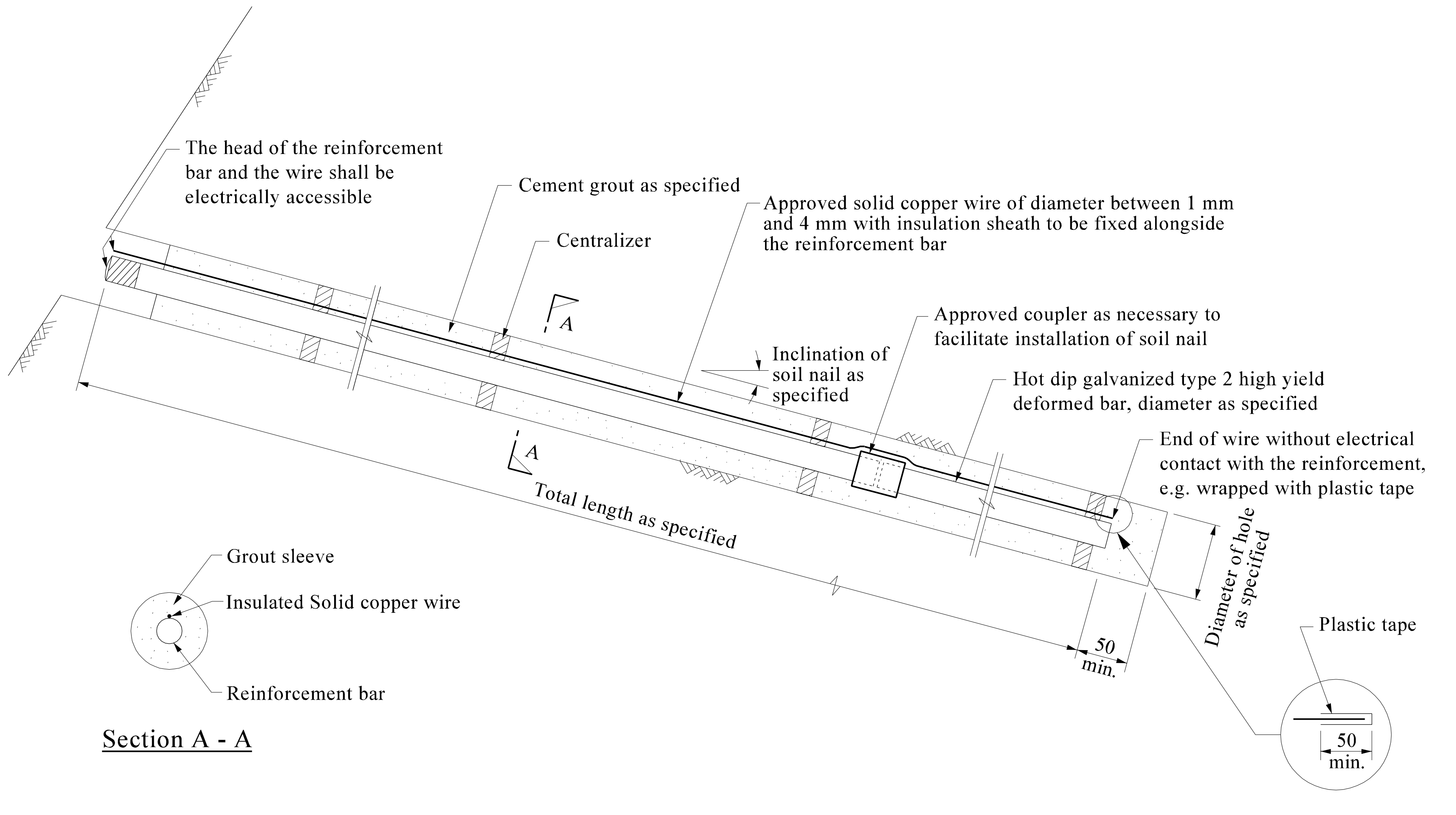
$$L = \frac{v_1 t}{2} = \frac{0.10084 \text{ x } 222.6}{2}$$

$$= 11.2 \text{ m}$$

Table of Contents

Table of Contents

Table of Contents



Note: All dimensions are in millimetres.

Figure A1 - Details of Provision of a Wire for Determination of Length of Soil Nail Reinforcement Using Time Domain Reflectometry

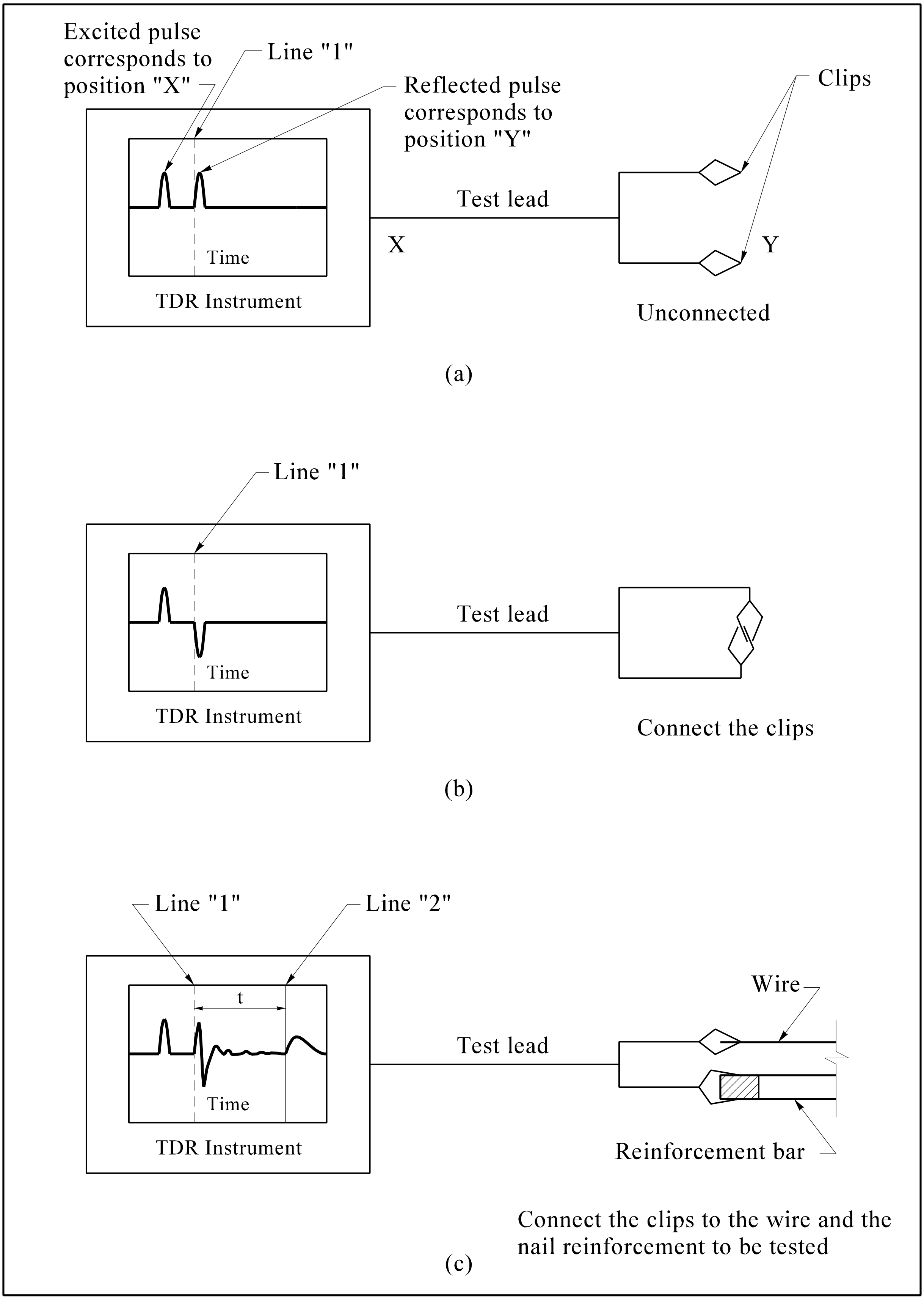
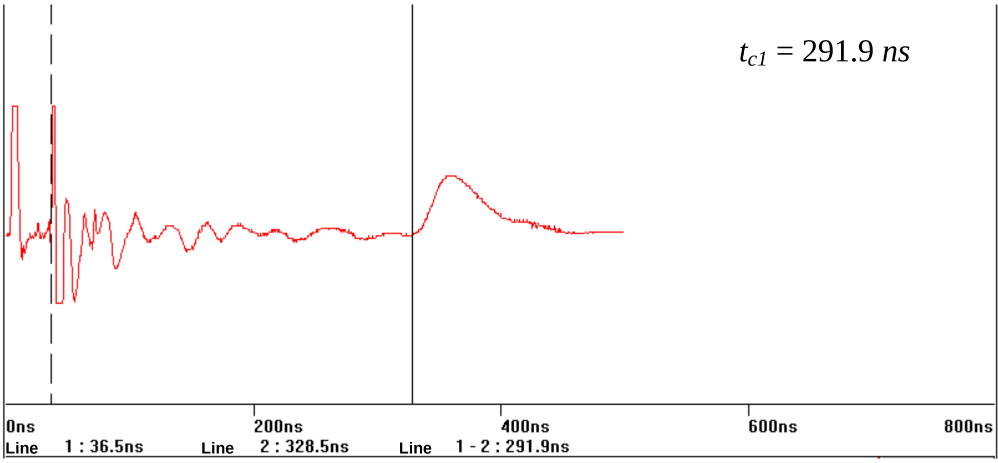
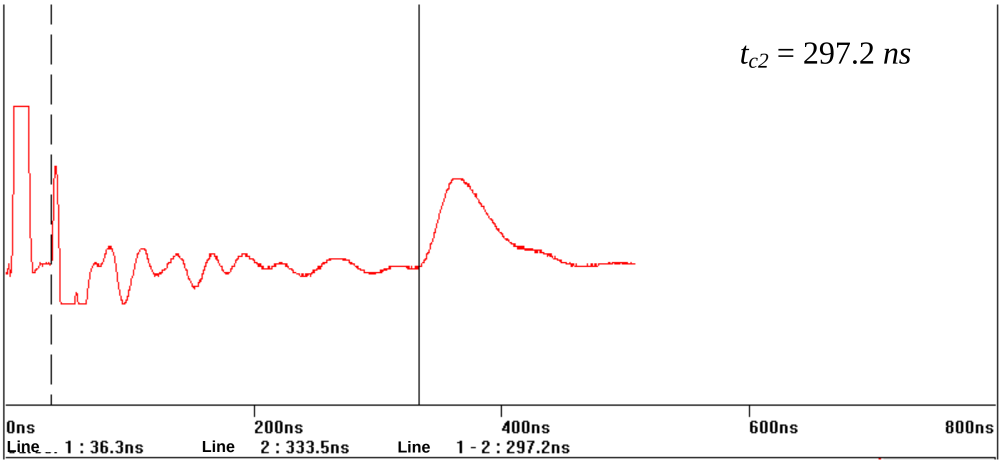


Figure A2 - Schematic Diagram Showing the Procedure of Using Time Domain Reflectometry for Determination of Length of Soil Nail Reinforcement

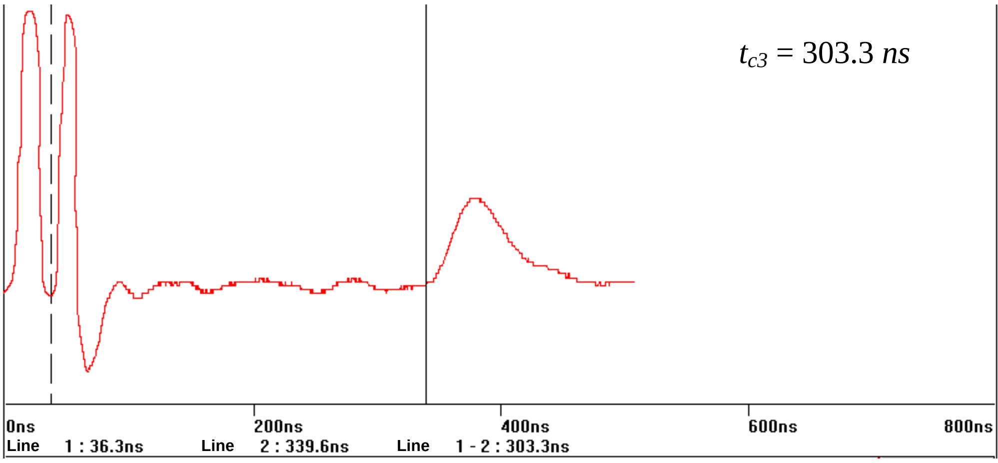
Table of Contents
Table of Contents
Table of Contents
Table of Contents



Pulse width < 5 *ns*



5 *ns* ≤ Pulse width ≤ 20 *ns*

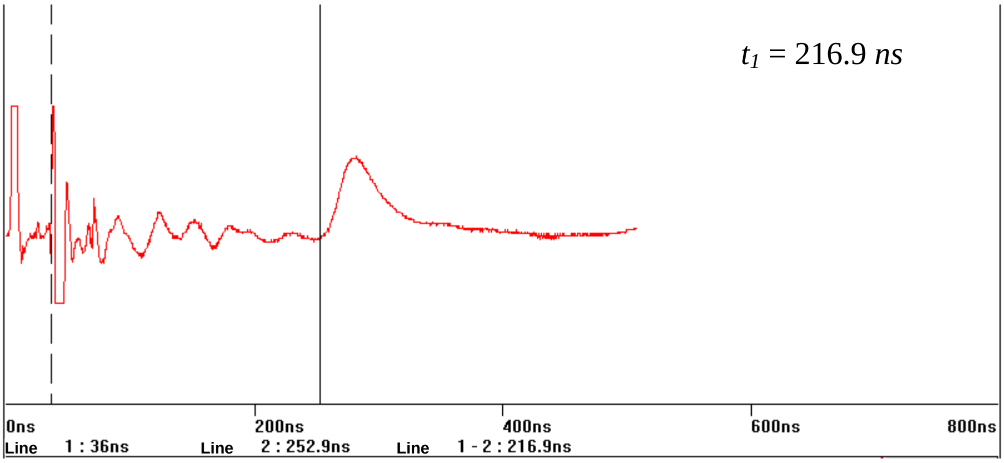


Pulse width > 20 *ns*

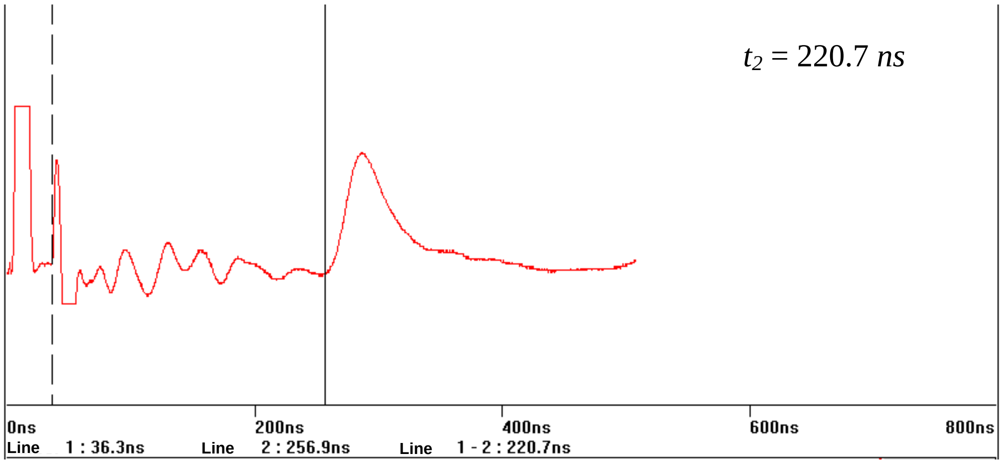
$$t_c = \frac{291.9 + 297.2 + 303.3}{3} = 297.5 \quad ns$$

Figure A3 - Results on Calibration Nail

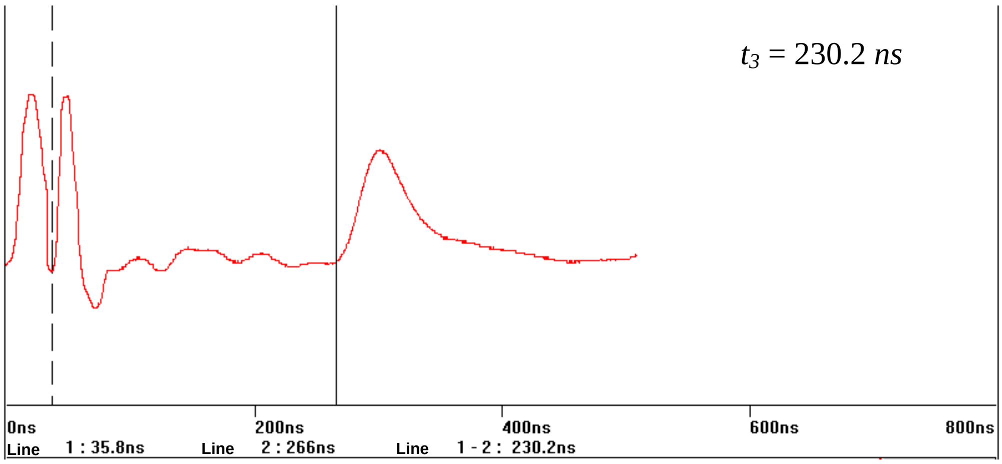
Table of Contents
Table of Contents
Table of Contents
Table of Contents



Pulse width < 5 *ns*



5 *ns* ≤ Pulse width ≤ 20 *ns*



Pulse width > 20 *ns*

$$t = \frac{216.9 + 220.7 + 230.2}{3} = 222.6 \quad ns$$

Figure A4 - Results on a Test Nail

Table of Contents
Table of Contents
Table of Contents
Table of Contents

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Table of Contents
Table of Contents
Table of Contents
Table of Contents

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土力工程處之主要刊物

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Geotechnical Manual for Slopes, 2nd Edition (1984), 300 p. (English Version), (Reprinted, 2000).

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The Quaternary Geology of Hong Kong, by J.A. Fyfe, R. Shaw, S.D.G. Campbell, K.W. Lai & P.A. Kirk (2000), 210 p. plus 6 maps.

The Pre-Quaternary Geology of Hong Kong, by R.J. Sewell, S.D.G. Campbell, C.J.N. Fletcher, K.W. Lai & P.A. Kirk (2000), 181 p. plus 4 maps.

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TGN 1	Technical Guidance Documents

Table of Contents
Table of Contents
Table of Contents
Table of Contents