REVIEW OF USE OF NON-DESTRUCTIVE TESTING IN QUALITY CONTROL IN SOIL NAILING WORKS

GEO REPORT No. 219

C.F. Lee and Ove Arup & Partners Hong Kong Ltd

GEOTECHNICAL ENGINEERING OFFICE
CIVIL ENGINEERING AND DEVELOPMENT DEPARTMENT
THE GOVERNMENT OF THE HONG KONG SPECIAL ADMINISTRATIVE REGION

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PREFACE

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

The Geotechnical Engineering Office also produces documents specifically for publication. These include guidance documents and results of comprehensive reviews. These publications and the printed GEO Reports may be obtained from the Government's Information Services Department. Information on how to purchase these documents is given on the second last page of this report.

R.K.S. Chan
Head, Geotechnical Engineering Office
December 2007

FOREWORD

This GEO Report is composed of two volumes, which were prepared under a study to review the use of non-destructive testing techniques in quality control in soil nailing works. Volume 1 presents the independent review conducted by Professor C.F. Lee, the Independent Technical Reviewer of the study. Volume 2 contains the final report on the study, prepared by Ove Arup & Partners Hong Kong Ltd.

W.K. Pun
Chief Geotechnical Engineer/Standards & Testing

VOLUME 1:
INDEPENDENT REVIEW OF USE OF NON-DESTRUCTIVE TESTING IN QUALITY CONTROL IN SOIL NAILING WORKS

C.F. Lee

This Final Independent Reviewer Report was prepared by Professor C.F. Lee of The University of Hong Kong in October 2007 under Consultancy Agreement No. GEO 05/2005

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PROJECT BACKGROUND

1. The lengths of soil nails constructed at three slope works sites were reported to be shorter than the designed lengths in the early 2000s. The incident led the Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department of the Hong Kong Special Administrative Region Government to search for means for better quality assurance for soil nail construction.

2. In 2002, a trial of five (5) non-destructive testing (NDT) in-situ techniques to evaluate the length of soil nails constructed was performed, and the results were reported in GEO Report No. 133. In 2003, a trial of three NDT techniques to evaluate the quality of grout surrounding soil nails was performed, and the results were reported in GEO Report No. 176 (Cheung and Lo 2005).

3. In mid-2004, GEO initiated a trial on the use of Time Domain Reflectometry (TDR) method, as supplementary measures, for quality control of soil nailing works at Landslip Preventive Measures (LPM) sites. Approximately 5,500 soil nails at 460 different LPM sites were evaluated using the TDR method up to the end of March 2006. The TDR method identified latent grout defects in some soil nails at two sites, allowing timely remedial works to be carried.

4. Ove Arup & Partners Hong Kong Limited (the Study Consultant) was employed by GEO under Agreement No. GEO 04/2005 to conduct a critical review of use of NDT techniques in quality control of soil nailing works and to formulate a framework for application of existing and/or newly developed NDT techniques for quality control of soil nailing works in future.

5. The specific objectives of the Assignment are: (1) to review and appraise the use of various NDT techniques in quality control of soil nailing works; (2) to formulate a general framework for application of NDT techniques for quality control of LPM soil nailing works; (3) to assess the suitability of the time domain reflectometry (TDR) method and other NDT techniques for use under the framework formulated and recommend how the techniques should be used.

6. Professor C.F. Lee of the Department of Civil Engineering of The University of Hong Kong was appointed by GEO as an Independent Reviewer on 19 June 2006 under Agreement No. GEO 05/2005 to steer and review the work of the Study Consultant.

7. The Final Report on Review of Use of Non-destructive Testing in Quality Control in Soil Nailing Works (Revision C) was submitted by the Study Consultant in July 2007.

8. This Final Independent Reviewer Report is submitted to the DR in compliance with Clause 5.2 of the Brief of the Agreement.

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INDEPENDENT REVIEW OF THE FINAL REPORT SUBMITTED BY THE STUDY CONSULTANT

9. The Final Report submitted by the Study Consultant includes a summary of the review conducted on the use of non-destructive testing (NDT) techniques in the assessment of soil nailing works; a review and appraisal of the TDR test data provided by GEO; a description of the quality control framework formulated for the application of NDT techniques in LPM works; recommendations on the requirements on testing techniques, sampling strategy, non-conforming threshold, and necessary follow-up strategy; and a presentation of the results of the assessment on the suitability of the TDR method and other NDT techniques for use under the framework formulated.

10. Seven NDT techniques have been reviewed and appraised by the Study Consultant. These seven techniques are: (1) time domain reflectometry (TDR); (2) electrical resistance method; (3) mise-a-la-masse (electric potential gradient) method; (4) vector magnetic method (magnetometry); (5) electromagnetic induction method; (6) sonic impulse method; and (7) surface wave time domain reflectometry (SW-TDR).

11. The fundamental theory, method of measurement, data interpretation, and state of development of each NDT technique were reviewed. For each technique, these factors were appraised to assess its operational value and cost-effectiveness: (1) the relative ease of deployment of the technique in Hong Kong; (2) the commercial availability of the equipment in Hong Kong; (3) the cost of the equipment; (4) the necessity to make specific modification and/or preparation of the technique for soil nailing works, and the extra costs associated, if any; (5) the technical integrity and reliability of the technique in the assessment of nail length and grout quality as constructed; and (6) the effectiveness of the technique to provide the results required.

12. The practical, theoretical, and equipment limitations of each NDT technique in soil nailing works were identified and tabulated by the Study Consultant. The table provides an excellent reference for engineers practicing in soil nailing works and developers of NDT techniques for applications in soil nailing works.

13. The findings from the review and appraisal of these seven NDT techniques at their current state of development are generally consistent with the conclusions and recommendations obtained by GEO in their independent trials and studies on these techniques as documented in GEO Report Nos. 133 (Cheung 2003) and 176 (Cheung and Lo 2005).

14. Three (3) sets of TDR test data were provided by GEO for analyses: (1) data of 704 initial tests that were used to assess the reliability and uncertainty of the TDR method; (2) data of 4,710 tests performed by testing contractors of the Public Works Central Laboratory; and (3) data of 1,224 tests performed by the Standards & Testing Division and District Divisions of GEO.

15. Pertinent data of the first set of TDR test data are the as-built lengths of soil nails and lengths deduced from interpretation of TDR test results from ten (10) different sites in Hong Kong. The pulse propagation velocities range from 0.0625 m/ns to 0.1018 m/ns. If the percentage difference in length estimation is defined by

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$$\text{Percentage difference in length estimation} = \frac{\text{Estimated nail length} - \text{As-built nail length}}{\text{As-built nail length}} \times 100\%$$

The mean and standard deviation of the percentage difference in length estimation are 0.44% and 4.26%, respectively. Moreover, the distribution appears to be a normal distribution. It should be noted that the statistical analyses are possible as both the estimated length and as-built length of each soil nail are known in this data set.

16. The 2nd and 3rd sets of data were combined in the statistical analyses. There are 5,777 test nails including 724 calibration nails constructed in 525 different sites. It should be noted that the length of the test nails, other than the calibration nails, have not been explicitly measured. Therefore, the Study Consultant performed five different statistical analyses: (1) use of the mean pulse propagation velocity of the calibration nail(s) of each batch of soil nails to deduce the lengths of test nails in the particular batch; (2) use of the median pulse propagation velocity of soil nails to deduce the lengths of test nails in the particular site; (3) use of the median pulse propagation velocity of all the test nails to deduce the lengths of all test nails; (4) use of the mean pulse propagation velocity of all the test nails to deduce the lengths of all test nails; and (5) use of the modal pulse propagation velocity of all the test nails to deduce the lengths of all test nails.

17. In the statistical analyses, the Study Consultant concluded that the data set cannot be adequately described by the normal distribution without excluding the extreme outliners. However, the Study Consultant has not included any plots on normal probability paper to demonstrate the extent of out-of-fit of normal distribution and how the fitness is improved by excluding the extreme outliners (Ang and Tang 1975). It is difficult to assess from Figs. 11(a), 12(a), 13(a), and 14(a) that the normal distribution does not describe the statistics of data adequately.

18. Various sources of uncertainties associated with the TDR technique have been analyzed by the Study Consultant statistically. These uncertainties have been identified by GEO (Cheung 2003, 2006; Cheung and Lo 2005). However, further study may be required to quantify these uncertainties explicitly for the TDR technique.

19. The framework for application of NDT techniques for quality control of LPM soil nailing works includes the components to be considered in the approval process of a NDT technique and the components in the implementation of a NDT program.

20. Components to be considered in the approval process include: (1) property to be measured; (2) primary requirements for acceptance as a quality assurance tool; (3) accuracy; and (4) reliability. Components in the implementation of a NDT program include: (1) sampling strategy; (2) alert criterion that triggers follow-up action; and (3) follow-up strategy including necessary contractual provisions.

21. The flowchart proposed by the Study Consultant is a very useful first step in the establishment of a framework for application of NDT techniques in soil nailing works. The preliminary applicability of the framework has been demonstrated by the Study Consultant using the TDR technique. However, the framework may have to be

refined through lessons learnt during the process, as many technique specific technical details may not be identified at this stage of development of the framework.

CONCLUSIONS

22. A review of use of non-destructive testing in quality control in soil nailing works has been conducted by the Study Consultant.

23. The findings of the Study Consultant have been reviewed independently. In additional to various discussions with the Study Consultant and GEO, the results of the independent review are reported in this Final Independent Reviewer Report.

24. All in all, I agree in principle with the findings and conclusions of the Study Consultant.

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VOLUME 2: REVIEW OF USE OF NON-DESTRUCTIVE TESTING IN QUALITY CONTROL IN SOIL NAILING WORKS

Ove Arup & Partners Hong Kong Ltd

This Final Report was prepared by Ove Arup & Partners Hong Kong Ltd in August 2007 under Consultancy Agreement No. GEO 04/2005

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FOREWORD

Ove Arup & Partners Hong Kong Limited (Arup) has been commissioned by the Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department (CEDD) to undertake Review of Use of Non-destructive Testing in Quality Control in Soil Nailing Works under Agreement No. GEO 04/2005.

This Final Report provides a summary of the review undertaken on the use of non-destructive testing (NDT) techniques in assessing soil nailing works, describes the quality control framework formulated in this Assignment for the application of NDT techniques in Landslip Preventive Measures (LPM) works, provides recommendations on the requirements on testing techniques, sampling strategy, non-conforming threshold and follow-up strategy and presents the results of the assessment on the suitability of the Time Domain Reflectometry (TDR) and other NDT techniques for use under the framework.

This study was carried out by Ms Dora Shum of Arup under the supervision of Dr Jack Pappin and Mr Peter Thompson. Valuable input was provided by Dr Frank Collar, the director of Cosine Ltd, particularly for the investigation and evaluation of various alternative NDT techniques that are available in the industry for use in quality control of soil nailing works. Valuable information and demonstration were provided by Mr P L Chak and Mr J M Shen of Geotech Engineering Ltd on the Sonic Impulse method. All contributions are gratefully acknowledged.

Dr Daman Lee
Director
Ove Arup & Partners Hong Kong Ltd

Agreement No. GEO 04/2005
Review of Use of Non-destructive Testing
in Quality Control in Soil Nailing Works

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EXECUTIVE SUMMARY

Ove Arup & Partners Hong Kong Ltd were commissioned by the Geotechnical Engineering Office (GEO) to undertake a review of the use of non-destructive testing (NDT) for the quality control of soil nailing works. The objectives of the Assignment are to review and appraise the use of various NDT techniques, to formulate a framework for application of NDT techniques in general for quality control of Landslip Preventive Measures (LPM) soil nailing works and to assess the suitability of the Time Domain Reflectometry (TDR) Method and other NDT techniques for use under the framework and recommend how the techniques should be used.

A framework for the application of NDT techniques in general for quality control of soil nailing works has been formulated in this study. The key components of the general framework comprise the components to be considered in approving a NDT technique for use in quality control of soil nailing works and the components for implementation of a NDT programme.

Under the proposed framework for the application of NDT techniques for quality control of soil nailing works, the "non-conforming threshold" is defined as the point below which anomalous result in the NDT measurement indicates that the soil nail is considered to fall short of the required construction specifications and follow-up investigation is warranted. The non-conforming threshold for different NDT techniques are different and are related either to the overall uncertainty of the NDT tests in deducing the length of the steel bar or to the probable maximum influence of variable ground. The threshold for NDT tests that are influenced by grout quality must be set prudently to avoid giving unnecessary false alarm.

It is proposed that a sampling plan based on the procedures documented in the BS 6001-1 (ISO 2859-1) be adopted for NDT techniques that provide a direct measurement of a property of installed soil nails. Using the sampling plan, soil nails are to be divided into various sample lots and selected for NDT tests. Follow-up investigation is warranted when the number of soil nails with anomalous NDT results in individual sample lots exceeds an "alert criterion". In such cases, all untested nails within the sample lot shall be tested and a design review should be carried out by the Engineer. Additional investigation by means of other NDT techniques or other methods would be required at this stage. Following the design review and additional investigation, the Engineer will decide in consultation with the Employer on whether additional soil nails shall be installed.

The proposed sampling frequency and alert criterion are set to achieve an acceptable quality level of 4% for soil nails passing the sampling plan and a consumer's risk of having 90% confidence in not accepting a sample lot with more than 20% non-conforming soil nails. The proposed customer risk is chosen to strike a balance between the testing frequency (i.e. additional cost and time) and the desired minimum quality level.

In respect of contractual provisions, all NDT tests are to be carried out by independent testing contractor and paid by the Employer. However, the Contractor shall provide the necessary safe access and work platform for all NDT tests. Further investigation and remedial works will be paid by Contractor only if it is proved that the anomaly is caused by defective construction (e.g. short nail or poor grouting practice). Otherwise, all costs will be

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borne by the Employer. Non-destructive tests are not yet recommended to be used as compliance tests because they do not provide proof of defective construction methods. Further, there is a concern that if the NDT tests are used as compliance tests, all follow-up actions would have to be made contractual and that would require every party to buy in to the test being reliable.

Since the commencement of the trial use of the TDR method on nails with pre-installed wires at the LPM slope works sites in mid-2004, about 700 controlled TDR tests on nails of known lengths had been conducted by the GEO and by the end of June 2006 a total of 5,777 soil nails at 525 LPM sites had been tested using the TDR method under the trial testing programme. Based on statistical assessments of the results from TDR trials at LPM sites, it is found that the use of the median velocity measured at a site in lieu of the velocity determined from a calibration nail is likely to provide more accurate results for the purpose of length measurement by TDR. By adopting the median velocity determined from the TDR test data obtained from each LPM site as the reference pulse propagation velocity to deduce the lengths of test nails at that site, the range of percentage length difference between the inferred value and reported value falls within –8.8% and +8.6% at 95% confidence level if a normal distribution model is used.

The accuracy and reliability of the TDR method on nails with a pre-installed wire to measure nail length have been proven with sufficient controlled tests and the statistical analysis of the TDR results obtained in the trial testing programme. A consistent basis for interpretation of the test results has also been established. The practical use of TDR method has been demonstrated in the trial testing programme. There were least four sites where the TDR tests had identified soil nails with significant grout defects. The TDR method is considered an effective method in detecting soil nails with significant defects in nail length or grout sleeve and the developments of the technique have satisfied the framework components for general use as a NDT technique.

In the existing framework for TDR, a 15% variation in the deduced length is used as a threshold that identifies soil nails with anomalous TDR test results. From the natural variance of TDR results, although there is room for tightening the threshold, more thoughts are required before doing so because the variation in the deduced length may be attributed solely to the difference in grout sleeve integrity between the calibration nail and the test nail. Some allowance for variability of the grout sleeve integrity is considered reasonable in order not to reject soil nails with minor grout defects.

For application of the proposed framework to TDR testing, consideration has been given to the testing regime that is commonly adopted on sites. If the proposed single sampling strategy is used (i.e. minimum sample size becomes 10 for each batch of soil nails), the use of median velocity is feasible and preferable to the use of calibration nails. As the value of the median velocity has to be unbiased for achieving acceptable accuracy in the TDR test, it is proposed that the median velocity should be compared with the mean velocity value obtained from a minimum of three calibration nails with enhanced supervision at each site. The critical stage of construction of these calibration nails should be observed by an engineer-grade supervisor. If the median velocity is more than 15% faster than the mean velocity value determined from the calibration nails, the mean velocity from the calibration nails should be used instead to estimate the lengths of the test nails. An alternative option is to simply adopt the average velocity determined from a minimum of three calibration nails.

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A flowchart and an example of a mock-up site are provided to illustrate how the proposed sampling strategy and modified testing regime could be applied in the case of TDR testing.

The use of grout pipes with embedded wires (two in each pipe) to replace the external wire for TDR testing has been investigated from which it was found that the variation of the results was reduced. The use of this method is found to provide more reliable results.

Apart from the TDR method, six other techniques have been considered in the review of the available NDT techniques used in quality control of soil nailing works and each technique has been assessed in terms of its relative merits and limitations from which it is found that several methods can be used to determine nail length but no NDT method can discriminate grout defects unambiguously. While the ability of most NDT techniques in the quantitative assessment of grout integrity of soil nails has not been reliably proven, the primary requirement for a proposed NDT technique for application in quality control of soil nailing works is the measurement of nail bar length. In their present forms, no NDT techniques, except the TDR method with pre-installed wire, have been developed to satisfy the framework components for general use in soil nailing works.

The Electrical Resistance method has been proven in practice that it can identify anomalous soil nails that are either significantly short in length or have significant grout defects but it is unable to discriminate between those two influences. The method can be used as a simple technique for testing large numbers of soil nails, particularly as a blanket reconnaissance approach in the event that all the nails are tested. It can also be deployed to help resolve anomalies shown by the TDR method (e.g. cases with no signal from nail end due to damaged wire or inverted reflection due to electrical contact between wire and nail bar).

The potential of several other methods may not have been fully explored and further directed development may be warranted. The Electromagnetic Induction method for example, in its present form, is not ideal due to the requirement to implant two tubes within the grout sleeve. However, the system may be able to be developed as a single coil system or as a spaced transmitter and receiver coil within a single plastic tube - to simplify the method and minimise practical constraints. In this respect the Electromagnetic Induction method could provide unequivocal results in nail length measurement provided that the construction of the plastic tube is practical and acceptable.

Similarly, by using the same provision of a single tube within the grout, the Vector Magnetic method may also be developed using miniature magnetometers to provide confirmation of the bar end without ambiguity from adjacent soil nails or influence by the grout, obviating the need for a separate borehole. In its present form, the Vector Magnetic method can only determine the length of shorter soil nails but the cost associated with the requirement of a separate borehole precludes its application on a regular basis.

The Mise-a-la-Masse method could in-principle be carried out simultaneously with the Electrical Resistance method to augment the characterisation of anomalous soil nails, but the practicability in application is yet to be proved in the field.

The other two methods, the Sonic Impulse and Surface Wave Time Domain Reflectometry methods are not proven standard techniques but are considered to have potential for further development given the possible value of the methods as a means of

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measuring soil nail length without additional provisions such as pre-installed wires or access tubes within grout sleeves. At their present forms, both methods rely heavily on interpretation of test results and lack a consistent basis/procedure for interpretation which should be made known for all users. For the Sonic Impulse method, until a post-processing method is well established and found to be reliable on a wide range of situations this method cannot be considered for general use.

The above potential modifications will have to be tested and appraised in a field application. Further, before these methods can be considered for general use, they will have to satisfy the requirements for proven accuracy and reliability under the proposed framework for application of NDT techniques for quality control of soil nailing works.

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1. INTRODUCTION

1.1 Background

Soil nailing has become one of the most commonly used methods for slope improvement works in Hong Kong; being a relatively straight forward, quick and cost-effective way to enhance the stability of slopes. However, concerns were raised on the quality of supervision on soil nailing works following reports of short nails being installed at three slope work sites in the early 2000s. These incidents led the Geotechnical Engineering Office (GEO) to look for means of better assurance of the quality of soil nails.

In 2002, GEO carried out a trial of five non-destructive testing (NDT) techniques to determine nail length, the results of which were reported in GEO Report No. 133 "Non-destructive Tests for Determining the Lengths of Installed Steel Soil Nails" (Cheung, 2003). In 2003, GEO carried out a trial of three NDT techniques for inferring grout quality of soil nails, the results of which were reported in GEO Report No. 176 "Interim Report on Non-destructive Tests for Checking the Integrity of Cement Grout Sleeve of Installed Soil Nails" (Cheung & Lo, 2005).

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In mid-2004, GEO started a trial use of the Time Domain Reflectometry (TDR) method with pre-installed wires, as a supplementary measure for quality control of soil nailing works at the Landslide Preventive Methods (LPM) slope works sites. By August 2004, about 700 TDR tests had been conducted. Based on the results of these 700 test nails over 9 different sites, GEO Report No. 198 (GEO, 2006) updated the experience gained on the use of this technique to determine soil nail length. The various sources of uncertainty of the TDR test were studied. These sources include human judgement in undertaking the test and subsequent interpretation of results, built-in error of the testing instrument, wire type, steel bar size and grout sleeve characteristics. In order to minimise the possible uncertainty of a TDR test, the installation details of the wire alongside a steel bar were standardised in the GEO Report. Guidelines on testing procedure and interpretation of TDR test results were also given. By the end of June 2006, a total of 5,777 soil nails at 525 LPM sites had been tested using the TDR method.

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In June 2006, Ove Arup & Partners Hong Kong Ltd (Arup) were commissioned by the GEO to undertake a review of the use of non-destructive testing in quality control in soil nailing works under Agreement No. GEO 04/2005.

An Independent Technical Reviewer, Professor C F Lee of The University of Hong Kong, has been employed under Agreement No. GEO 05/2005 to steer and review the work of Arup in this study.

1.2 This Report

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The requirements of this report are to:

(a) summarise the review on the use of NDT techniques in assessing soil nailing works and the experience gained and issues encountered;

(b) describe the quality control framework formulated in this Assignment for the application of NDT techniques in the LPM works;

(c) describe the implementation of the framework and define the action of the various parties under the framework;

(d) provide recommendations on the requirements on the testing techniques, sampling strategy, non-conformance threshold and follow-up strategy;

(e) present the results of the assessment on the suitability of the TDR method and other NDT techniques for use under the framework.

2. REVIEW OF THE USE OF NDT TECHNIQUES IN SOIL NAILING WORKS

2.1 General

The main NDT methods which were originally investigated by GEO in 2002 for determining lengths of steel soil nails include the following:

(a) Sonic Echo Method;

(b) Mise-a-la-Masse Method (Equipotential);

(c) Magnetometry;

(d) Electromagnetic Induction Method; and

(e) Time Domain Reflectometry (TDR).

The findings of the above investigation were documented in GEO Report No. 133 (Cheung, 2003). While considering Magnetometry and TDR as the most suitable methods among the five trial methods for application in existing soil nailed slopes, GEO Report No. 133 also highlighted that further investigation was needed to develop their accuracy and reliability. For new soil nailed slopes, it was recommended to install plastic tubes or electric wires along with the steel nails and to allow the use of the Electromagnetic Induction or TDR methods respectively for quality control. Subsequent to the study, GEO started a trial use of the TDR method with pre-installed wires at the LPM slope works sites in 2004.

In a later study undertaken by GEO, three NDT techniques including the Sonic Echo method, Surface Wave Time Domain Reflectometry and the Electrical Resistance method were identified for field trial to check the integrity of the cement grout sleeve. The findings of the study were presented in GEO Report No. 176 (Cheung & Lo, 2005). Based on the above study, it is considered that the Electrical Resistance method has the highest potential for field application. However, the method cannot explicitly distinguish the type of defects, which may be in the form of grout defects or atypically short steel bar. Nevertheless, the Electrical Resistance method was regarded to be promising as a quick,

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convenient and economical means to aid identifying soil nails that have significant grouting defects.

Subsequent to the above studies, trial use of TDR for routine checking of soil nail lengths has been carried out in the GEO LPM works since 2004. The Electrical Resistance method (ERM) is occasionally used for grout integrity checks when the TDR results are uncertain. Vector Magnetic Profiling (equivalent to Magnetometry in GEO Report No. 133) has been used on a few sites for length checks where the TDR showed significant anomalies. This method however requires a separate parallel drillhole along the length of the soil nail to be checked.

In the study reported here, the available information and data on the use of the NDT techniques have been reviewed and appraised. Seven NDT techniques have been considered, which include:

(i) Time Domain Reflectometry (TDR);

(ii) Electrical Resistance Method;

(iii) Mise-a-la-Masse Method;

(iv) Vector Magnetic Method (Magnetometry);

(v) Electromagnetic Induction Method;

(vi) Sonic Impulse Method; and

(vii) Surface Wave Time Domain Reflectometry (SW-TDR).

The principle and the use of each of the NDT techniques to assess the quality of soil nailing works are described in the following sections. Each NDT technique has been assessed in terms of its relative merits and limitations in five categories in terms of the operational value of the method and its cost-effectiveness. These categories are as follows:

(a) Practical issues - the relative ease with which the method can be deployed routinely;

(b) Equipment - the commercial availability and cost of the measuring equipment;

(c) Extra costs and provisions - the necessity to make specific preparation for the soil nail under test beyond the measurement procedure;

(d) Theoretical considerations - the technical integrity of method in terms of its reliability to respond to the length of the steel bar or the deficiency of the grout sleeve without external factors being introduced;

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(e) Value of results - the effectiveness of the method to provide the required results.

In addition, a Limitations Table (Table 1) has been drawn up to provide a basis for comparison.

2.2 Time Domain Reflectometry (TDR)

2.2.1 Fundamental Theory

Time Domain Reflectometry (TDR) is a well-established technique in electrical engineering for detection of faults in transmission lines. 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 or discontinuities in the line.

The configuration of a soil nail is analogous to a coaxial cable if an electric wire is pre-installed along a steel soil nail (Cheung, 2003). The propagation velocity of an electromagnetic wave, V_p , travelling along a coaxial cable is given by:

$$V_p = \frac{1}{\sqrt{(L \cdot C)}}$$

where L is the cable inductance in henries per metre and C is the capacitance in farads per metre. Inductance is the property that will induce electric field in one conductor due to the change of electric current in another or in itself. Capacitance is the amount of charge (quantity of electrons) stored across a physical system in relation to the imposed electric field and is dependent upon the geometry and dielectric property of the system. The dielectric property is the ability of a material to store electric charge under the influence of an electric field and is a fundamental material bulk property. Fundamentally therefore, the propagation velocity V_p is controlled by the dielectric property of the materials in close proximity to the conductor pair, i.e. the grout and the wire insulation, by the following expression:

$$V_p = \frac{V_c}{\sqrt{\varepsilon}}$$

where V_c is the speed of light in vacuum (3 x 10^8 m/s) and ε is a dimensionless number called dielectric constant which compares the permittivity in a material and that in vacuum (for air $\varepsilon \approx 1$, for grout $\varepsilon \approx 10$ and for water $\varepsilon \approx 80$). Changes in the nature of any of those materials in close proximity to the conductor pair will effect some change on the dielectric property and hence also upon the propagation velocity and the capacitive and resistive impedances. Theoretically, the propagation velocity in air is 3 times faster than that in grout and the velocity in water is 3 times slower than that in grout.

The width of the applied TDR pulse is in nanoseconds. In fact the pulse can be considered as a summation of a wide spectrum of continuous frequencies with no phase offset at the pulse centre and with different amplitudes. Hence a short TDR pulse (2 ns) will have a greater proportion of higher frequency spectrum components than a 30 ns pulse width.

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The velocity of propagation will vary according to the frequency (higher frequencies tend to travel faster but incur greater attenuation). Therefore the propagated and reflected pulse will incur progressive frequency component dispersion and higher frequency component attenuation along the nail / wire coupled system, resulting in a stretched, rounded and asymmetric return pulse. It also accounts for the observed variation of measured "group" velocities from a 2 ns pulse width (usually faster) to a 30 ns pulse width (usually slower). Under the current practice, in order to achieve consistency in determining the travel time of the reflected TDR pulse, "time zero" is taken at the onset (i.e. rise of waveform) of the observed pulse and its reflected return. A typical TDR response (of 2 ns pulse width) for a steel soil nail with pre-installed wire is shown in Figure 1.

The amplitude and polarity of the reflected TDR pulse is controlled by the factor called the coefficient of reflection k_e as follows:

$$k_e = \frac{(Zg_e - Zs_e)}{(Zg_e + Zs_e)}$$

where Zg_e is the impedance as seen looking out from the ends of the conductive couple and Zs_e is the impedance of the system looking back from the ends of the conductive couple. Hence an insulated wire end (fully taped) will result in a high Zg_e and the reflection coefficient tends to unity, i.e. positive total reflection. An electrical join between the bar and the wire will reduce the value of Zg_e resulting in reduced reflected amplitude. When Zg_e is less than Zs_e the reflected pulse assumes negative polarity (k_e is -ve) and for the ends of the conductors in direct metallic contact, the reflection coefficient k_e is -1, i.e. total reflection with negative polarity as shown in the waveforms in Figure 2. The form of the expression for the reflection coefficient is common to electrical, sonic (sound and seismic), optical, electromagnetic environments.

Impedance is the effective resistance to current transients (e.g. TDR pulse or continuous alternating current) and has three components, namely the resistive, capacitive and inductive components. The total electrical impedance is given by the vector sum as follows:

$$Z_e = \left[\left(\omega \cdot L - \frac{1}{\omega} \cdot C \right)^2 + R^2 \right]^{0.5}$$

where ω is the frequency of the current transient and L, C and R are the inductance, capacitance and direct current resistance of the circuit system respectively.

2.2.2 Method of Measurement and Data Interpretation

The test configuration of the TDR method is considered to be analogous to a twin-conductor transmission line. In practice, an electrical pulse is excited to the soil nail being tested and the major pulse reflection, which records the time for the pulse to travel from the nail head to its end, is identified. If the pulse propagation velocity is known, the length of the soil nail can be determined on the basis of the recorded pulse propagation time.

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The test basically comprises two operations:

(i) Calibration of pulse propagation velocity for a particular nail and wire arrangement; and

(ii) Measurement of the time for a pulse to propagate from the steel bar head to its end.

Calibration of the pulse propagation velocity has traditionally been achieved by selecting a series of ‘calibration nails’ at each site. The purpose of the calibration nail is to determine the pulse propagation velocity which can be used to determine the length of test nails at the same site using 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. However, it should preferably be the longest nail among the test nails because the resolution on the interpreted travel time of a pulse along a long nail is comparatively higher than that for a shorter nail for a given testing instrument.

The velocity of the TDR pulse is calculated as the period from pulse onset time at the nail head connector to onset time of the reflected pulse divided by twice the length (down and up the wire) of the nail / wire conductor couple. As mentioned in Section 2.2.1, this is a “group” velocity of a wide band of frequencies. In current practice the velocity V_p is calculated at the “calibration nail” of known length for two pulse widths (2 ns and 10 ns) and then applied as an average to the nails under test to calculate their length.

For a steel soil nail of length L, the time required for the TDR pulses and their echoes to travel a distance of 2L is $(t_1 - t_0)$. Thus, the length of the steel soil nail is:

$$L = \frac{V_p \cdot (t_1 - t_0)}{2}$$

where t_0 is the time of pulse excitation and t_1 is the time of arrival of the response.

According to the standardised procedures set out in the GEO’s document called “Guidelines on Test Procedure and Sample Test Results Using Time Domain Reflectometry (TDR) to Determine the Length of Installed Soil Nails”, both t_0 and t_1 are picked at the positions where the reflected pulse corresponding to the clips of the test lead and the end of the nail respectively starts to rise as illustrated in Figure 1.

2.2.3 Practical Issues

The TDR method has been subjected to a comprehensive set of controlled laboratory and site tests by GEO and the overall integrity of the method is shown to be upheld in general. The inter-observer reliability of the test has been proven in repeatability and reproducibility tests. The uncertainties associated with the use of the TDR method were investigated and the results were reported in GEO Report No. 198 (Cheung, 2006) wherein the procedure for conducting and interpreting TDR test have been standardised.

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The test measurement and interpretation for the TDR method are relatively simple. Hence, an operator with suitable training can perform the tests satisfactorily without difficulty.

On the other hand, the accuracy of the TDR method depends on the proper installation and material consistency of the electric wire. If the pre-installed wire is damaged and in electrical contact with the steel bar (at a location other than the bar end), an early inverted wave reflection will be resulted with no reflection from the nail end (Figure 2), giving an inconclusive result.

Controlled TDR tests have been carried out by GEO in both laboratory and site conditions to simulate a wide range of possible conditions with respect to wiring configurations and wire types. From these tests, it was demonstrated that coiling of the wire may result in overestimation of actual soil nail length. However, as this way of fiddling with the wire configuration is rather obvious and hence the chance of being noticed by the supervision personnel would be high. It is therefore considered that this mal-practice would rarely be attempted.

In one of GEO's special investigations, the use of grout pipes with embedded wires to replace the external wire for TDR testing has been investigated in controlled tests and the results show that the variation of pulse propagation velocity is generally less than that measured using external wires. This would mean that the error band for length estimation could be reduced by use of this type of grout pipe with embedded wires. The development of the use of embedded wires in grout tube would effectively diminish the possibilities of fiddling with wire configurations. The results of this special investigation are discussed in detail in Section 3.3.

2.2.4 Equipment

The TDR equipment has become commonly available since the trial use of the technique in LPM works. There are at least three private testing laboratories which can perform the test and in accordance with the guidelines set out by GEO.

2.2.5 Extra Costs and Provisions

In general the method is not greatly expensive and the special provision is the wire to be cast into the soil nail. Normally, it is taped to the bar during installation.

2.2.6 Theoretical Considerations

As explained in Section 2.2.1, the TDR test is somewhat sensitive to grout sleeve integrity through its effects on the dielectric property and hence upon the pulse propagation velocity and the capacitive and resistive impedances. As a result, the TDR method is not able to determine nail length unequivocally. However, it is not a detriment as both grout and length deficiencies will result in anomalous TDR results that could lead to follow-up actions.

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The return signal of the TDR test is the convolution of the two-way impulse with the wave reflections from grout defects and nail end. Hence, it may include second order responses which should not be attributed to individual grout defects. The interpretation of waveform in terms of grout integrity is therefore largely qualitative.

There is a weakness with the current practice of selecting a single calibration nail. There is no guarantee that the calibration nail is typical for other nails. In practice problems do occur because the ground conditions vary and so does the grout quality and hence velocities may vary amongst the nails even at close spacing. It may be better to consider using the mean (or median) velocity for a group of soil nails or increasing the number of calibration nails. The same weakness applies to the Sonic Impulse and SW-TDR methods which also require site calibration to determine the reference propagation velocity. Targeting this weakness, the testing regime for the TDR method has been reviewed in this study based on the test data collected from the trial use of TDR in the LPM works and the details are provided in Section 3.1 and Section 5.2.

The method is not influenced by adjacent soil nails.

2.2.7 Values of the Results

From the statistical analyses undertaken on the initial TDR tests (over 700 no. of tests) that were conducted on soil nails of known lengths, the overall error in length estimation was estimated to be approximately ± 8% at the 95% confidence level. This has proven that the evaluation of the soil nail length using the TDR method is usually possible unless there are extreme grout defects.

Since the commencement of the trial use of the TDR method on LPM sites, there have been at least four sites where the TDR tests performed had identified soil nails with significant grout defects. The grout defects were verified with the use of extraction or other NDT methods including the Electrical Resistance method and the Vector Magnetic method. On one of the sites, the grout defects are considered to be due to an underground void which was revealed at a subsequent investigation by closed circuit television survey.

2.3 Electrical Resistance Method

2.3.1 Fundamental Theory

The Electrical Resistance method measures the electrical resistance between the soil nail and the whole surrounding space, which is a function of the soil nail and grout column length and the electrical resistivity of the surrounding ground.

As a simplified concept, the measured earth resistance of a soil nail can be considered as comprising five distinct components as depicted in Figure 3(a). They are:

(a) the resistance of the nail bar;

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(b) the contact resistance (conversion between electronic and ionic conduction mode) between the galvanised plating of the soil nail and the cement grout;

(c) the radial resistance to the ionic current across the grout annulus as a thick cylinder containing the soil nail;

(d) the radial resistance to the ionic current through the ground as a very thick cylinder around the grout sleeve; and

(e) the resistance to the ionic current through the ground as a hemispherical component, divergent beyond the end of the installed soil nail and the grout.

The resistance of the nail bar (a) will be negligible compared with the other resistance components, unless significant rusting has occurred on the threads of the coupler joints. Resistance (b) is the resistance of the electrochemical conversion between electronic conduction in the nail bar by electron flow and the electric conduction in the grout by ionic migration. It will be inversely proportional to the total area of the grout sleeve that is in direct contact with the soil nail, and therefore for correct installation also inversely proportional to the length of the soil nail. Resistance (c) is a function of the grout resistivity, the outer and inner radii of the grout annulus and is also inversely proportional to the length of the grout sleeve. The radial resistance (d) of the ground beyond the grout may be expressed as a function similar to (c), that is, directly proportional to the resistivity of the weathered material and inversely proportional to the length of the soil nail. The hemispherical ground resistance component (e) beyond the end of the soil nail may be expressed as a constant term that is simply a function of the divergent ionic conduction through the ground and hence also a function of the ground resistivity, but it is not a function of the soil nail length.

The greatest contribution to the total resistance is incurred over the closest radii from the source (i.e. the current density is greatest), which, for a soil nail, includes the grout annulus. Consequently a moderate grout defect may be expected to have significant influence upon measured resistance. The resistivity of grout is approximately 10 ohm·m. The resistivity of ground water is approximately approx 100 ohm·m and the resistivity of air is infinitely large. Over the section of grout deficiency, the resistance will increase in proportion to the ratio of the infill material resistivity to grout resistivity. A grout gap will therefore tend to increase the resistance significantly because the grout radius is small.

The Resistance R is fundamentally inversely proportional to the length. In practice the toe end of the grout will have some contribution, adding a constant to the inverse linear relationship, but it is comparatively small.

2.3.2 Method of Measurement and Data Interpretation

The method of measurement applies a current to the soil nail as one current electrode and returns the current through a distant small current electrode (typically 60 - 80 metres away). The system uses alternating current to avoid polarisation of the electrodes.

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As shown in Figure 3(b), a third electrode is sited approximately midway between the soil nail under test and the remote current electrode and it measures the voltage (electric potential difference) between the soil nail and the electrically neutral background. The measured voltage V between the potential electrode and the nail head allows the resistance R_e to be calculated through the equation:

$$R_e = \frac{V}{i}$$

where i is the current. In fact the calculation is performed directly by the equipment which gives a direct reading of R_e. From the electrode configuration and the form of the electric potential distribution as shown in Figure 3(b), R_e is reasonably taken to be the resistance between the nail bar and the whole earth (zero potential). Measurements are conveniently grouped along soil nail rows as individual profiles, in which 10 or more measurements are preferable to establish background levels, or the measurements can be grouped in clusters sufficient to generate a resistance map.

The Electrical Resistance method operates in a comparative mode by measuring the resistances of a sequence of close spaced nails and determining those which have anomalously high resistances. For isolated occurrences, this may be attributed to abnormal reduction of current emission due to grout deficiency or to an abnormally short soil nail. Anomalously low resistances are probably due to grout excess but a low resistance condition is not common.

The ground is not homogeneous and variations of resistance may occur from local geological contrasts of ground resistivity. However, although the lateral contrasts of ground resistivity may be locally abrupt, the consequent variations of resistance tend to be smooth between closely spaced soil nails because the current radiates in all directions. The profile resistance data can be filtered with a controlled wavelength filter that is based upon the probable maximum influence of a corestone or a step in rockhead (Figure 4(a)). The geological influence affects adjacent nails so a smooth variation usually applies whereas an anomalous individual nail is definitely indicative of some deficiency.

In all of the test measurements it is necessary to define the threshold level that determines unacceptable "abnormality". The levels of measured resistance are influenced by the surrounding ground as well as the nominal soil nail length. In order to be objective in any site environment, discrimination is currently achieved by application of a simple comparative statistical measure. By this method, the scatter of values along each row is defined as a variance upon a smoothly variable background trend as shown in Figure 4(b). The criterion for acceptance is for any one resistance value to be within two positive standard deviations on that trend.

2.3.3 Practical Issues

Electrical resistance measurement is usually quite efficient in terms of simplicity of measurement and speed of coverage, once the remote electrode wires have been laid out. Two remote, fixed electrodes are deployed, the soil nail under test forming the third electrode. Once planted, the remote electrodes usually can remain undisturbed for the whole group of soil nail rows to be measured.

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The remote electrodes are positioned at distances of approximately 60 to 80 metres for the current electrode and 30 to 40 metres for the "potential" measuring electrode. In fact the distances are not critical and can be less but they should be arranged generally in line such that the full distribution of soil nails to be measured does not reduce the minimum distance to the potential electrode to less than 20 metres for any nail. Effects due to variable distances are gradual and do not influence the comparison of resistances from nail to nail. If the remote current electrode cannot be placed practicably at a large distance, it is feasible to adopt a soil nail in a distant part of the same site for that purpose.

The electrical connections comprise two wires between the remote electrodes and the measuring instrument, plus the short connection to the soil nail under test. Direct electrical contact with the cleaned nail head is preferred. Loosely wrapped wire contact may introduce some small resistance error or reading instability.

The operation can be conducted by junior technical staff. The method is fast once the system is set up and only limited data analyses is needed. Commonly the results are available immediately on site by direct observation of the measurements.

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2.3.4 Equipment

The equipment required for these electrical resistance measurements is commonly available as three electrode ground resistance measuring devices, routinely deployed for measuring the resistance of earthing or grounding stakes of electrical power installations and major buildings. The equipment may be purchased through most major electronics supply companies. A resistance measurement resolution of 3 significant figures is required.

2.3.5 Extra Costs and Provisions

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The method requires no special provisions other than a connection to the nail bar head. In practice, wire connections to the head are often poorly made and therefore a direct clip connection onto the head is preferred, i.e. measurements ought to be made prior to casting the concrete head. Further, sufficient space must be available to position the remote electrodes.

2.3.6 Theoretical Considerations

The method does not respond directly to the nail end from which length can be determined. Rather it is a remote measurement that is inversely related to the length of contact between the steel bar and the ground, including the grout sleeve. Therefore, the method cannot discriminate between a bar deficiency and a grout deficiency but it is able to identify a soil nail that may be problematic in comparison with adjacent soil nails.

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The theoretical basis for the method is reasonably well understood to the extent that the influence of variable conditions, either of the grout or of the ground, is readily predictable. A grout deficiency diminishes the available path for current emission and therefore effectively increases the resistance. Hong Kong groundwater and soils are usually more resistive (resistivity usually more than 150 ohm·metres) than grout (resistivity approximately 10 ohm·metres) and therefore the high resistance condition for grout deficiency will persist with saturated ground although diminished compared to grout void filled with air. The local presence of shallow rock will also introduce a corresponding rise in resistance but the effect cannot be abrupt between adjacent nails. Hence a background filter can be applied to eliminate the maximum influence of rock from the data, if required where a group of nails may be anomalous. Soil nail drillhole records are particularly useful in that respect.

In practice the electrical resistance data are repeatable usually to within 0.2%. Any variation outside that level for repeat measurements on an individual soil nail usually indicates a poor connection to the nail head.

Variable ground, especially a shallow variable rockhead will influence the results and hence some smooth variations in the data over several adjacent nails have to be recognised within controlled limits. But individually discrepant data are positive indications of deficient soil nail installations.

The method is largely unaffected by the presence of adjacent nails. However, it is not viable for soil nails with double corrosion protection.

2.3.7 Value of the Results

As a comparative method, the Electrical Resistance method cannot be readily assessed in terms of accuracy of results (in terms of length). Instead it must rely upon a statistical measure to provide a datum for evaluating the significance of the results. The method responds to the soil nail bar length and also to the integrity of the grout sleeve but it is unable to discriminate between those two influences. In practice this may not be a detriment as both constitute a defect.

The sensitivity of the method has been investigated practically on site by Cosine Ltd through two routes. The first approach used the resistance data for incremental grout sequences of the pull-out nails. The second compared the residual resistance data of working installed soil nails that are known to be physically shorter than the adjacent soil nails by design. Predictably, the sensitivity to deficiencies decreases with increasing soil nail length. The sensitivities calculated during test measurements on installed soil nails and pull out soil nails on one site indicated that the method was capable of discriminating grout deficiencies of 1 metre in a 9 metre nail length and 2 metres in a 15 metres length. However, these are optimum levels derived from not a significant amount of data and may not be achieved necessarily in all cases as the sensitivity of the method appears to vary from site to site due to soil nail length and geological differences, and possibly also with depth of the grout and the position of the void within the grout. To be effective the method is dependent upon a low standard deviation in the natural scatter of the data. Nevertheless, the results are sufficiently consistent at this stage to suggest that the method could be developed with a greater number of supporting data to provide a generalised quantified estimation of grout or soil nail length deficiency.

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The method is potentially useful as a simple technique for testing large numbers of soil nails, particularly as a blanket reconnaissance approach in the event that all the nails are tested. To that extent it can provide useful support to the established TDR method to provide some form of measurable discrimination, by setting thresholds of permitted resistance variance.

2.4 'Mise-a-la-Masse' (Electric Potential Gradient) Method

2.4.1 Fundamental Theory

As discussed in GEO Report No. 133 (Cheung, 2003), the method is based on the principle that when electrical energy is applied to two points through electrodes in the ground, an electric current will flow between them because of the potential difference. If the ground between the two electrodes is homogeneous, the electric current and potential distribution can be calculated by means of a theory. However, if the electrode is replaced by a steel soil nail and/or the ground is heterogeneous, there will be distortion of the electrical field. If the distribution of the distorted electrical potential is calibrated against steel soil nails of known lengths, the length of a test nail can be estimated theoretically by recording the distribution of potential around the nail at the same site.

2.4.2 Method of Measurement and Data Interpretation

Electric current is admitted to the soil nail head and is returned through a remote current electrode. As deployed in the original trials carried out by GEO in 2002, the distribution of the surface electric potential was measured between a roving potential electrode and the soil nail bar head in a radial pattern about the soil nail head as shown in Figure 5(a). The objective was to determine the length of the soil nail by the form of the electric potential distribution which is calibrated against soil nails of known lengths. In practice the sensitivity of this approach is very low and it is subject to variation due to the attitude of the soil nail in relation to the slope surface and to the variations of ground resistivity.

2.4.3 Practical Issues

The 'Mise-a-la-Masse' method is in effect a detailed implementation of the Electrical Resistance method and it can be carried out using the same setup and simple resistance equipment. The method was originally conceived to determine the length of the soil nail and many measurements were specified to measure the electric potential distribution around each nail accordingly. The testing process is very time-consuming and efficiency of the method was relatively low. The accuracy demonstrated so far was unsatisfactory for the test purpose, hence the method was not considered further.

2.4.4 Equipment

The same equipment that is deployed for the resistance measurements can be used directly and with suitable resolution. The equipment is therefore readily accessible and relatively low cost.

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2.4.5 Extra Costs and Provisions

The method requires no special provisions other than a connection to the nail bar head. In practice, a poor wire connection to the bar head will result in a depression of the surrounding potential gradient and therefore a direct clip connection onto the head would be preferred, i.e., it would be better to take measurements prior to casting the concrete head.

2.4.6 Theoretical Considerations

Closely related to the resistance method, the 'Mise-a-la-Masse' measurements are responsive to the whole length of the installed soil nail as a linear current emitter. As a consequence, and as theoretical studies conducted in this study have demonstrated, the method may be capable of discriminating between head end and toe end grout deficiencies, provided those deficiencies are significant.

Adopting the reasonable simplification of uniform current emission, the theoretical basis is straightforward but the method would be directly subject to the influence of variable ground conditions. As a result, it would be better deployed in a comparative mode with statistical qualification rather than attempting any form of individual calibration which was fundamental to the original concept.

The method may be affected slightly by the adjacent soil nails, which will tend to influence the 'vertical' potential profile in the local vicinity of the target nail in the event of significant grout deficiency. This would be expected because the adjacent electrically conductive bar would traverse the "vertical" potential gradient and incur some longitudinal current flow. This effect will need to be investigated in tests but could possibly be used to advantage when selecting the ground surface measurement points.

2.4.7 Value of Results

The 'Mise-a-la-Masse' method is subject to ground conditions as well as to the nail characteristics. The high variability of ground resistivity affects the accuracy of this method. Ground resistivity is defined as the inverse of electrical conductivity of the ground. Its value depends on a number of parameters including moisture content, salt content, temperature, etc. Statistical evaluation of variance over several nails may therefore be more appropriate in this case. Even so, depending on the adopted radial distances of the resistance gradient measurements in relation to the nail head, the method is expected to be slightly less sensitive to bar or grout deficiencies than the Electrical Resistance method.

2.4.8 Potential Modifications

If the 'Mise-a-la-Masse' method were to be applied in a comparative mode, rather than attempting an absolute definition, it may then be possible to devise a single potential gradient (voltage or resistance) measurement that achieves discrimination adequately and rapidly. Quite simply, this measurement could take the form of a resistance measurement between the nail head and a radial distance of (say) one or two metres distance (or both), effectively

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substituting the remote potential electrode in the resistance measuring circuit.

Theoretical studies carried out for this study suggest that this modified form of the method may have some application for discriminating the states of grout deficiency as shown in Figure 5(b). Treated comparatively between nails, the measurement could be applied to discriminate grout loss at the upper or lower section of anomalous nails.

Hence if the potential measurements are confined to a horizontal profile through the soil nail head and the results are treated on a comparative basis rather than attempting absolute evaluation, it may provide a useful qualification to the Electrical Resistance method.

It is recommended that the method should be subjected to further investigation and potentially could be deployed selectively on those nails that are discriminated initially by the more rapid reconnaissance resistance method. The technique could be more appropriately termed the "Electric Potential Gradient" method. Similar to the Electrical Resistance method, the individual accuracy of measurements cannot be considered because it is subject to ground conditions as well as to the nail characteristics.

2.5 Vector Magnetic Method

2.5.1 Fundamental Theory

Soil nail steel bars have varying degrees of strong permanent magnetism, probably induced during the hot roll manufacturing process. Thus, by measuring the fluctuation of Earth's magnetic field in the vicinity if a soil nail, the presence of a steel bar can be identified. The dominant permanent magnetism takes the form of poles at some position within each individual nail segment. Initially it is assumed that the polarisations are at the segment ends as shown in Figure 6(a). In order to detect the end of an installed steel soil nail, it is necessary to provide a drillhole parallel to and in the vicinity of the steel nail for insertion of an instrument called magnetometer (Cheung, 2003). In practice, however, the method is not as straightforward as it seems because the polarisations at the physical ends may in fact be small.

For a magnetic pole of strength m the magnetic potential at distance r is +m/r. The magnetic field intensity I at distance r from the pole is $-m/r^2$, that is, it acts toward the pole. If the field is measured along a profile in a parallel hole passing the pole, then with reference to the Figure 6(b), the vector components of the polar field are given by:

Axial vector component (usually z direction): $\dfrac{-m}{r^2} \cdot \cos\beta$

Perpendicular to the axis (usually x and y vector component sum): $\dfrac{-m}{r^2} \cdot \sin\beta$

where β is the angle of incidence of the polar field and the vector direction at the measurement point.

The theoretical forms of the magnetic vector profiles recorded as the magnetometer probe descends the measurement hole and β varies between -90 and +90 are shown in Figure 6(b). Usually, although not necessarily for all equipment, the vector magnetometer measures the field component m_z parallel to the axis, and m_x and m_y perpendicular to the axis.

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The measurement procedure is to lower (or raise) the magnetometer probe in the test hole and record the profiles of m_x, m_y and m_z. In practice it is difficult to restrain the probe from rotating axially within the hole so it is convenient to combine the m_x and m_y vectors after measurement as:

$$m_{xy} = \sqrt{m_x{}^2 + m_y{}^2}$$

Maximum changes of responses are observed as the magnetometer sensor passes the pole, that is where the distance r is least. Hence for a segment magnetised at its physical end, the last recorded pole position implies the end of the nail.

2.5.2 Method of Measurement and Data Interpretation

In the present form, the Vector Magnetic method requires a test drill hole to be prepared closely adjacent to the soil nail under test and cased with PVC tube. Ideally the test hole should be approximately 2 metres longer the soil nail design length. A magnetometer probe is lowered down the hole, usually with the aid of detachable drain rods to ensure that it penetrates fully to the bottom.

The vector magnetometer measures the magnetic field as three orthogonal vector components (m_x, m_y and m_z), one of which will be axial to the hole and the other two in the perpendicular plane. The magnetometer is winched to the surface recording the three magnetic profiles against depth continuously in digital form on a controlling laptop computer. The zero depth of the magnetic sensor element relative to the nail head must be established to ensure correct depth recording by the digital odometer. The magnetic profiles are then analysed to indicate the point at which the magnetometer passes and responds to the adjacent toe of the magnetic soil nail.

The initial test measurements showed that the position of the last main polar response was commonly less than the known length of the nail bar under test. Subsequent tests on uninstalled bars showed that the dominant magnetic polarisation does not necessarily occur at the end of the nail but may be significantly inset by more than a metre in some cases - the amount varying from segment to segment. This is most probably because the segments are cut after the magnetisation has been assumed in the manufacturing process.

However, due to the magnetic permeability of the steel bar, the magnetic field of the polarization will tend to be concentrated axially so that a secondary but weaker polarisation is induced at the nail end where the magnetic flux emerges and diverges. This in effect results in a weaker but detectable polarisation at the physical end of the soil nail. Simple processing has been developed to detect this secondary polarisation.

The first derivative (dm_z/dz) of the m_z profile is essentially a single peak with two small side lobes where it passes a pole. The second derivative (d^2m_{xy}/dz^2) of the m_{xy} profile is also a single peak with two small side lobes for a pole. The product of the two functions (dm_z/dz) · (d^2m_{xy}/dz^2) will tend to reinforce sharply where the probe passes a pole whereas it will tend to zero for non-polar conditions.

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This simple diagnostic function can be successfully applied to the recorded profiles to detect the weaker polar physical end conditions. The local magnetic properties of the ground are usually far too weak to have any influence upon the results. The process method by means of a diagnostic function as described above is effective at detection of the weaker secondary end polarization with an accuracy of 0.25 metres or better regardless of the main polarisation location (see Figure 6(b)).

2.5.3 Practical Issues

The approach attempts to contrast the magnetic characteristic along the length of soil nail bar with the magnetically quiet conditions beyond the toe and hence to locate the end of the bar. To do this it requires magnetic measurement over a significant part of the target soil nail length, within an adjacent prepared borehole and for at least two metres beyond the soil nail end. The prepared borehole must therefore exceed the design length of the soil nail by at least two metres.

The Vector Magnetic method is not practically efficient, requiring at least 30 minutes per soil nail to set up then record the full magnetic profile. Further, the method usually demands more than one operator depending upon the nature of the equipment and at least one technically skilled operator is necessary. Subsequent data processing and analysis are then required.

Simple inexpensive and available equipment to conduct the measurements can be devised but the time required for measurement is extended. Magnetic logging equipment (used for the original tests undertaken by GEO) reduces the measurement time significantly but it is expensive and not commonly available.

The major drawback of the method is the uncertainty of the test borehole alignment in relation to the installed soil nail under test. This limitation is especially relevant to soil nails longer than 10 to 12 metres beyond which the borehole could become closer to an adjacent soil nail with consequent misleading magnetic results.

A refinement of the method was devised and tested to eliminate this uncertainty by measuring the magnetic profile with an introduced magnetic induction (magnet admitted to the nail bar head) then repeating the measurements with the magnet reversed. The difference between the two measured profiles theoretically eliminates the influence of all adjacent soil nails leaving only the influence of the applied magnet itself (×2) and the induced polarization (×2) at the end of the soil nail. Although a positive result was obtained, the refinement was found to be impractical, partly due to depth accuracy constraints but mainly because polar induction at the toe end of the bar was found to be extremely weak. The weak induction would be expected if the permanent magnetic polarisation of the steel was close to its natural magnetic saturation limit (the hysteresis limit).

To summarise, the method suffers several major practical limitations:

(a) The method requires a separate test hole.

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(b) Soil nails are typically 1.5 to 2 metres apart. Except for short (e.g. 12 metres or less) nails, there is a real possibility that the test hole may transgress to an adjacent nail.

(c) Magnetic induction with reversal has been applied to discriminate the soil nail under test and was moderately successful but the technique is time consuming and the magnetic properties of the steel bar may also be at or near to saturation level. Thus induction at the far end of the soil nail may be inhibited.

2.5.4 Equipment

The equipment used for the initial tests is not commonly available and is generally confined to the mining exploration sector. Sources of commercial vector magnetic logging equipment are known in Canada and Australia and are posted on the Internet. The costs are relatively high compared with the equipments of other NDT methods.

2.5.5 Extra Costs and Provisions

The method at its present form requires preparation of a plastic cased borehole, which would be prohibitive on a regular basis. The method is therefore considered inappropriate for routine tests.

Access to the nail bar head is not required.

2.5.6 Theoretical Considerations

Provided the measurement borehole can be drilled in close alignment with the soil nail under test, the method does respond to the end of the installed bar as the point at which the magnetic profile of the bar finally collapses. It therefore provides a direct indication of length unaffected by grout or ground conditions.

However, the dominant magnetic polarisation of the bar recognised in the raw data typically may not occur at the bar end. But suitable processing of the combined magnetic vector profiles enhances the weak secondary polarisation sufficiently to observe the end condition. However, the technical process is likely to be beyond the normal facilities available to a technical operator and requires software specific to that application.

2.5.7 Value of Results

The method provides a direct estimate of the bar length. The results are repeatable but the uncertainty of the borehole and soil nail alignment, including adjacent soil nails, effectively limits this method to the shorter soil nails. Comparison with soil nail design lengths on measurements conducted so far indicate that the accuracy of the method is usually

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of the order of +/-0.25 metres.

Acceptable confidence in the results is therefore restricted to shorter soil nails and cost considerations effectively preclude application on a regular basis.

2.5.8 Potential Modifications

Small economic solid state vector magnetic units are manufactured commercially and are readily available through major electronics suppliers. They can be suitably adapted for operation in water filled test holes. It may be possible to adapt the solid state sensor chips for insertion into a grout sleeve tube for close direct access to the soil nail end, in which case the limitations listed above would be negated. However, this modification is subject to some uncertainties including the potential adverse effect from the provision of an access tube to the grout sleeve integrity and the possibility of a kink along the tube which may impede insertion of the solid state vector magnetic unit.

2.6 Electromagnetic Induction Method

2.6.1 Fundamental Theory

Electromagnetic systems are deployed for metal detection in many industrial applications, mining exploration and perhaps most commonly in security devices. Fundamentally the systems operate by transmitting an electromagnetic field which will interact with any nearby electrical conductors. The conductors in turn radiate a secondary electromagnetic field that can be detected either by direct comparison with the primary transmitted signal or by monitoring the phase distortion induced upon the total combined field. The presence of the conductor can therefore be detected by monitoring the change in response and the degree of response is directly related to the electrical conductivity. Hence the electromagnetic systems are highly sensitive to the presence of metals, which in contrast to the ground and the grout are good conductors.

As shown in Figure 7(a), an alternating current i_t passing through a conducting primary coil T_x will generate an axial magnetic field H_t (flux) that alternates in phase with the current. If a second coil R_x is admitted nearby, the intersecting component of the alternating magnetic flux H_{tr} will induce an electromotive force (emf) in that coil, with a resultant current i_r if the coil circuit is closed. The secondary emf (voltage) is greatest when the rate of change of the intersecting magnetic flux dH_{tr}/dt is maximum, that is, as the alternating current in the primary coil oscillates through zero. Hence by that inductance, an emf signal can be measured in the secondary receiver coil which, in the absence of other influences, will show a phase contrast of -90 degrees when compared against the emf signal of the primary coil.

In the close presence of a steel bar, induction will occur between the primary coil and the conductive steel and secondary induction will also occur between the steel bar and the secondary coil. The magnetic coupling H_{tb} between the primary coil and the steel bar induces eddy current i_b in the bar which, due to the high conductivity of the steel, will be significantly out of phase with the current of the primary coil T_x.

The out of phase eddy current i_b further generates a secondary magnetic flux, equally

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out of phase with the primary flux, and a component of that secondary flux couples as H_{br} with the receiver coil R_x. Thus the total magnetic coupling on the receiver coil R_x in the presence of the steel bar then becomes the sum of H_{tr} and H_{br}, which will be significantly out of phase with H_{tr} and will differ in amplitude. Both the phase and amplitude of the flux sum will depend upon the electrical conductivity of the steel and the physical separations between the coils and the steel.

By monitoring the induced response in the receiver coil R_x as a comparison with the primary applied signal to transmitter coil T_x, the close proximity of steel, and hence the physical end of the steel bar, can be accurately gauged through the changes of phase and amplitude as the transmitter and receiver coils move past the bar end.

The presence of the enclosing grout medium will also influence the characteristics of the electromagnetic system. Grout is an ionic conductor although very much less conductive than the steel bar. Therefore it will also incur a weaker induced secondary ionic current through inductive coupling with the transmitter coil. But due to its more resistive property the phase change of the induced current will be less in the grout than that of the steel and, subject to the applied current frequency, it will attenuate the coupling coefficient between the coils and the steel bar. Consequently in a uniform grout sleeve the influence of the grout annulus upon the receiver signal will remain constant and unrecognized whereas in variable grout conditions some small modifications of phase and amplitude may be expected.

2.6.2 Method of Measurement and Data Interpretation

Electromagnetic induction is a common method of geophysical prospecting for electrically conductive minerals, the presence of metals and contrasting ground resistivity. This application to soil nails is conceptually identical and the method was developed by the Public Works Central Laboratory of the Civil Engineering and Development Department. The assessment below is based primarily upon the descriptions given in GEO Report No. 133 (Cheung, 2003).

In the deployment described by GEO, small transmitter and receiver coils are lowered simultaneously in open plastic tubes that are preset in the grout sleeve. The transmitter coil emits an electromagnetic (AC) signal that is detected by the adjacent receiver coil throughout the soil nail length profile. The two signals are monitored continuously at the surface on an oscilloscope or equivalent equipment. The signal returned by the receiver coil is influenced in phase and amplitude, dominantly by the presence of the steel bar. As the coil devices pass the end of the steel bar together, the receiver signal is significantly modified by the change of inductance, resulting in an observable change of amplitude and phase. The observed change indicates the end of the steel bar.

The initial electromagnetic tests conducted by GEO yielded the most accurate results of all test methods for determination of the bar length. In principle this is mainly due to the facility of detecting the contrast at the end of the bar in close proximity rather than reliance upon a response system that is subject to physical conditions along the length of the bar (e.g. TDR and sonic reflection or by detection in a distant test drillhole). Surrounding ground conditions would be unlikely to distort the result significantly. However, to achieve that measurement the method inherently requires special provision in the form of access tubes.

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2.6.3 Practical Issues

As described, the method requires two plastic tubes to be inserted with the grout at the time of installation. For soil nail length testing, small coils wound on narrow mild steel formers are lowered in the two tubes simultaneously. An AC signal is introduced to one coil as a transmitter (primary signal) and the other acts as a receiver. Ideally the coils should remain in a constant geometric relationship. The practical issue of admitting and maintaining the coils together in routine surveys therefore demands careful control. The profile measurements are therefore not particularly efficient.

Measurements are required over a profile to contrast the response in the presence of the steel bar with the response in its absence beyond the soil nail end. At present it appears that no provision is made to record the data profile against depth for subsequent reference but that determination of the end of the nail is by direct visual inspection of an oscilloscope signal trace on site. Modification to that system is warranted for practical application.

2.6.4 Equipment

At present there is no commonly known commercially available equipment for this specific application. Geophysical equipment operating on the same principles for ground investigation are commonly available but are designed for surface, airborne or larger diameter borehole use and are inappropriate in this application.

The electromagnetic system deployed in tests so far by GEO relies upon the transmitter and receiver coils admitted separately in two parallel tubes either side of the steel bar. These have a possible impact of two plastic tubes upon the integrity of the grout sleeve.

2.6.5 Extra Costs and Provisions

The two plastic tubes set in the grout introduce an extra provision and may also have detrimental effect upon the integrity of the grout sleeve. At present it is not clear how the tubes extend beyond the nail end other than by extension of the soil nail drillhole and grout.

2.6.6 Theoretical Considerations

The two coils are mutually inductive so that the receiver coil registers a (secondary) signal that is induced directly by the transmitter coil. The presence of the steel bar introduces a further inductive coupling which results in reduced amplitude of the receiver signal and will also cause phase shift between the primary and secondary signals. As described, the present set up detects the point (the depth in the tubes) at which the induction of the steel bar ceases to influence the secondary signal, hence identifying the end of the soil nail.

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2.6.7 Value of Results

The Electromagnetic Induction method provides a direct measurement of the steel bar length of the soil nail. It is possible that it may also respond to grout deficiencies (as amplitude changes without phase shift). Surface geophysical electromagnetic equipment is already available for this type of application (void detection). The potential capability of this method is high provided the construction of the plastic tube(s) is practical and acceptable and previous test records already indicate a high level of accuracy.

2.6.8 Potential Modifications

Coupling between the steel bar and the coils is dependent upon their physical separation and upon the orientation of the coil axes. It is feasible to arrange the two coils co-axially within a single tube, separated at a small distance, for example similar to the diameter of the grout, to achieve a measurable response (see Figure 7(b)). The signal response of the receiver coil would tend to be dipolar, superimposed upon the amplitude step response, as each coil passed the end of the steel bar, providing a similarly clear diagnostic condition for bar end recognition.

A single coil (and hence single tube) would register the presence of the steel bar as a distinct primary voltage phase lag (against primary current), with amplitude depression. The modified method would be expected to give a usefully clear response to the end of the steel bar beyond which there would be zero phase shift and restored amplitude. Such a system would obviate the need for two tubes.

In general, electromagnetic signals at higher frequencies emitted from smaller coil dimensions incur greater attenuation in adjacent conductive materials. As such they would be expected to be increasingly influenced by the presence or absence of the moderately conductive grout. In principle therefore, there may be an option with the Electromagnetic Induction method to develop a system that provides some selective evaluation of the grout integrity as well as the nail bar length. It is envisaged that this may be achieved through application of dual frequencies and switch selectable coil dimensions on the probe device.

Hence, two coils separated by a few centimetres on a single former as illustrated in Figure 7(b) should equally provide sharp definition of the bar end and, subject to the coil separation, could also provide a useful indication of grout integrity. However, it should be noted that these potential modifications have not been appraised in a field application. The single tube system is, at a lesser degree, still subject to the same drawbacks of the two tube system which include the potential adverse effect of the tube to grout integrity and possible kink along the tube which could potentially obstruct penetration of the coil(s).

Comparisons of signal phases and amplitudes would seem to be too complex an issue for routine site measurements and would demand a relatively high level of operator expertise. However, as evident with most security scanning devices, the method would lend itself to direct electronic evaluation which could trigger an audible sound at a threshold level as the bar end is passed.

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2.7 Sonic Impulse Method

2.7.1 Fundamental Theory

The sonic impulse, imparted manually by a hammer tap to the nail bar head, propagates down the length of the soil nail assembly and is reflected from the toe end to return to the head. The total travel time of the impulse and its reflection is directly proportional to the length L of the soil nail through the relationship:

$$T = \frac{2L}{V}$$

where T is the total recorded travel time and V is the propagation velocity of the impulse in the soil nail. With previous knowledge of the velocity, either by calibration or adoption of an average value, the length of the soil nail can be calculated directly.

The signal reflection at the toe of the soil nail occurs as a function of the contrast of acoustic impedance properties of the soil nail (Zs_a) and the containing ground (Zg_a) where k_a, the acoustic reflection coefficient, is given by:

$$k_a = \frac{Zg_a - Zs_a}{Zg_a + Zs_a}$$

where acoustic impedance Z_a is the product of velocity and density.

2.7.2 Method of Measurement and Data Interpretation

The Sonic Impulse method requires no special site provision other than direct access to the soil nail bar head and it responds directly to the length of the soil nail. To that extent the method is attractive but in practice it is subject to several complications.

The technique uses standard pile testing sonic reflection equipment. For soil nails with relatively small bar sizes (e.g. 25 mm), a small socket as shown in Figure 8(a) is attached to the soil nail bar head to provide sufficient area for both attaching the sensor element and hammering the soil nail bar head. The impulse is imparted to the socket by the impact of a light hammer or steel pin as shown in Figure 8(b). Figure 8(c) shows the various types of hammers and pins that were tried initially, which were subsequently reduced to 5 as suitable for continued use (Chak & Shen, 2006). The sensor and equipment records the initial impact impulse and the subsequent signature of the reflected sonic responses. In most cases, data processing is required in order to be able to identify the reflection from the soil nail end. The total travel time of the end reflection is then measured from the processed waveform signal.

Various data processing techniques have been employed in the Sonic Impulse method for determining soil nail lengths. The ones that are routinely used include:

(a) Filtering off the unwanted signals and vibrations by use of a high frequency filter (generally above 1 kHz as a first step);

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(b) Magnification of the response by application of an exponential function to compensate for soil damping and attenuation; and

(c) Identification of the first reflection wave from the nail end by detecting its distinct features (e.g. amplitude, characteristic jerk, repetition of initial wave pattern etc).

Figure 8(d) presents an example of the data processing procedure which was adopted in one Sonic Impulse test conducted on a 12 m long soil nail.

2.7.3 Practical Issues

Although ideal in concept, the Sonic Impulse method may suffer in practice from several factors, the effects of which tend to obscure the returning sonic signal such that unequivocal definition of the travel time is not always possible or is difficult. Those factors are a direct consequence of the convolution of the propagating impulse signal with the variable and unpredictable physical characteristics along the length of the soil nail.

Signal attenuation will occur progressively as a result of normal energy absorption and of lateral refraction loss into the containing ground throughout the length of the soil nail. This attenuation will have greatest influence for long soil nails.

The acoustic impedance of the soil nail is a function of the combined elastic properties of the steel bar and the grout and it will vary for variable grout conditions, either for significant excess or deficient grout. The propagating impulse will be partially reflected by those variable conditions, adding apparently spurious responses to the recorded signal and diminishing the onward propagating signal in both the forward and return directions.

The sonic impulse comprises a wide spectrum of frequencies. The higher frequencies travel at slightly greater velocities than the lower frequency components and they are also subject to greater attenuation. Hence the returning impulse will tend to become a signal ‘train’ and the main impulse tends to become longer and less distinct. This may not present a problem in many cases, especially for shorter soil nails but for longer soil nails where the reflection is weak and the signal is diminished through attenuation, the central pulse may be difficult to discriminate, potentially leading to significant errors of travel time definition.

The acoustic reflection coefficient k_a determines the amplitude and polarity of the returning pulse. If the properties of the ground at the termination are similar to those of the soil nail, as may occur with some states of rock, then the reflection coefficient will tend to zero resulting in a very weak or negligible signal return. The developers have recognised this condition and claim to have minimised it by attachment of a plastic shoe to the steel bar end. The effectiveness of this is not proven however as the signal is likely to have dispersed into the rock with very little signal actually reaching the steel bar end.

Tests conducted so far have shown that the signals are prone to high frequency noise, presumably a resonant frequency of the soil nail that tends to obscure the required return

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impulse signature. The developers have minimised the effect by application of a low pass (1800 Hz) digital filter although the impulse response of the filter is not known.

The test does not appear to be difficult to apply although some small preparation of the soil nail head appears necessary to be able to impart the pulse. It does require a person of high technical experience to analyse the data including selective processing. The data processing procedure for the test has not been standardised. Depending on the quality and characteristic shape of the original waveform, the amount and forms of the processing techniques to be applied may need to be varied in each test in order to be able to identify the reflection from the soil nail.

The time required for each measurement will be slightly greater than for TDR measurements and additional time is required for processing. The efficiency of the method in its present form is therefore not expected to be high.

2.7.4 Equipment

The equipment is commercially available as seismic pile length testing units and requires modification only to the method of imparting the sonic (seismic) impulse. The characteristics of the available input and gain filters may be an issue considering the short travel times and development is still ongoing.

2.7.5 Extra Costs and Provisions

The attraction of the method is that it addresses the length of the bar directly but does not require any additional pre-preparation of the soil nail, either by drillhole, wire or tube. In that respect it is unique amongst all of the methods proposed so far. Access to and minor preparation of the soil nail bar head is required.

2.7.6 Theoretical Considerations

The method is responsive to the length of the soil nail, expressed as the total travel time of the sonic pulse. It therefore offers a direct evaluation of the length.

It is technically straightforward in concept, although it apparently demands considerable post-processing to overcome the poor signal to “noise” ratios. The “noise” may derive from multiple reflections from couplers, source ‘ringing’ and possibly through variable grout contact.

The signal will be attenuated by progressive signal refraction loss through the grout to ground and signal (frequency) dispersion during the travel time would also be expected, diminishing accuracy of measurements on longer soil nails by stretching the reflected primary impulse into a signal ‘train’ and progressive attenuation of high frequencies, resulting in loss of definition. Therefore a limiting soil nail length can be expected beyond which reliable results might be precluded.

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In principle though, the method will not be affected by laterally variable ground other than probable effect upon signal attenuation. In that respect, deficiencies in grout are less likely to have a significant effect on the test result.

The method is subject to determination of a calibration velocity with resultant scope for significant error. Possibly this might be overcome by a statistical evaluation of velocities on any given site, selecting the median velocity to be adopted universally.

The method is not influenced by adjacent soil nails.

2.7.7 Value of Results

The developers indicate that the waveform is not always repeatable. This does seem to be a fundamental weakness that could diminish its value in present form as an acceptable standard test method. The only variable condition that could cause the non-repeatability is the method of impulse generation. Some further development would therefore seem worthwhile in that area.

The consistency or reliability of length measurement has not been assessed and is subject to the observations of the tester in picking the reflected pulse. Until a post-processing method is well established and found to be reliable on a wide range of situations this method cannot be considered further.

2.7.8 Potential Modifications

According to the published account by the developers (Gectech Resources & Geotech Engineering Ltd), the impulse characteristics are not always repeatable. This lack of repeatability must derive from the manual impact, the hammer blow, which is the only variable factor. Hence significant improvement may be effected by development of a fixed mechanical or electro-mechanical device, possibly including a piezo-electrical device, which could impart an impulse with controlled constant characteristics. The facility may help reduce the high frequency ringing and also provide facility for signal ‘stacking’ or summing to improve final recorded signal amplitude and improve signal to noise ratios.

2.8 Surface Wave Time Domain Reflectometry (SW-TDR)

2.8.1 Fundamental Theory

The method of electromagnetic Surface Wave Time Domain Reflectometry (SW-TDR) is being developed commercially by Supreme Instruments Ltd for investigation of soil nails and other structures in Hong Kong. Other than the claimed results published by the developers of this application (Tang, 2004 and Tang & Yim, 2005), few details of the method have been released or made available for detailed discussions. The assessment below is based primarily upon the published information on the method.

Alternating signals, for example an electromagnetic pulse, tend to propagate near to the surface of the conductor to which they are admitted. The phenomenon is commonly

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recognised as the skin effect in wider geophysical applications, a property that is a function of conductivity, inductive permeability (inductance per meter) and frequency. Hence an electromagnetic pulse applied to a soil nail bar will tend to propagate close to the outer surface of the bar as shown in Figure 9(a). In its propagation along the surface of the bar, the wave will be subjected to the variable inductive and capacitive properties imposed by the adjacent grout sleeve (or absence of grout) in relation to the assumed electrically neutral surrounding space.

Those variations of inductive and capacitive properties present a variable impedance profile along the length of the bar that is subject to the frequency components of the pulse, and they will result in a train of signal reflections accordingly. Figure 9(b) shows an idealistic impedance profile for a soil nail with anomalies along the rebar (Tang, 2004). In practice, the recorded returning signal represents the two-way convolution of the electromagnetic pulse with the impedance sequence, similar in principle to the pulse propagation of the established TDR method and the Sonic Impulse method.

The developers attempt to define the impedance sequence attributed to the grout column by measurement of the potential and current amplitudes of the returning signal.

2.8.2 Method of Measurement and Data Interpretation

Details of the operational system have not been released. Essentially it is a time domain electromagnetic system similar in operational principle to the equipment currently deployed on the routine TDR tests on soil nails, that is, it admits an electromagnetic pulse to the nail bar head. The method differs essentially from the established TDR technique by avoiding the use of a parallel wire to create the inductive - capacitive ladder. It seems in this case that some form of background reference would still be necessary though to complete the inductive - capacitive reference and therefore an earth line is expected.

The equipment has been designed to measure both the potential and the transient current of the return signal, from which the designers derive the impedance train directly. They attribute the calculated impedance train to the impedance sequence of the soil nail, qualitatively relating observed changes of calculated impedance with states of grout integrity.

As presented in the relevant publications, interpretation of the calculated impedance sequence in terms of grout integrity is largely qualitative and to that extent does not differ from the established method of TDR commonly deployed in Hong Kong at present.

The results published so far do show a marked response for the end of bar / grout condition, from which a length determination can be made provided a calibration velocity is available. However, standardized procedures for interpretation of the test results are not provided in the published information. Figure 9(c) shows one of the published test results for a ground anchor (Tang, 2004).

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2.8.3 Practical Issues

The principal difference and advantage that this method would offer over the standard TDR method is avoidance of the pre-installed wire. The method would therefore be suitable for measuring existing soil nails where a pre-installed wire was not provided.

The published tests to date show consistent length responses for soil nails of the order of 12 metres long. The response from longer nails appears to be untested although the indicated strength of responses in the published data suggests that the length determination may apply usefully for lengths significantly greater than 12 metres. No inconclusive results have been presented so far.

2.8.4 Equipment

Commercial equipment may not be available to date and the prototype equipment used in Hong Kong is proprietary and no details have been released. It appears that the basis of the equipment is fundamentally similar to the standard cable testing TDR equipments with the added provision of a means to monitor and record the transient current.

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2.8.5 Extra Costs and Provisions

Similar to the Sonic Impulse method the SW-TDR technique would be attractive as a means to determine soil nail length without the necessity for added provision to the soil nail installation.

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2.8.6 Theoretical Considerations

The designers of the SW-TDR method attribute the calculated impedance train to the impedance sequence of the soil nail, qualitatively relating observed changes of calculated impedance with states of grout integrity. However, some caution may be necessary in that procedural step because the return signal and hence the derived impedance train are in fact the convolution of the two-way impulse with the actual impedance sequence. The derived impedance train therefore will include second order responses which should not be attributed uniquely to individual grout defects. All TDR systems, electromagnetic or sonic, for investigating grout states would be subject to that complication. An important step is to identify the signal that corresponds to the reflection from the bar end, which relies heavily on interpretation.

The method is not influenced by adjacent soil nails.

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2.8.7 Value of the Results

The potential value of the method as a means of measuring soil nail length without additional provisions seems good, subject to sufficient accuracy and reliability trials. However, for the method to be cost effective, it is likely that fully developed equipment would have to become readily available in the commercial market. A consistent basis of interpretation of test results is also needed.

The method has a potential for grout integrity evaluations.

2.9 Summary of Findings

From the review, it is found that several methods can be used to determine nail length but no NDT method can discriminate grout defects unambiguously. Although the inferred nail length from TDR is somewhat sensitive to the quality of the grout sleeve, the accuracy and reliability of the TDR method with a pre-installed wire to measure nail length have been proven in practice. In fact, there have been at least four cases where the TDR tests performed on LPM sites have identified soil nails with significant grout defects. This TDR method is considered an effective method in detecting soil nails with significant defects in nail length and grout sleeve and the developments of the technique have satisfied the framework components for general use as a NDT technique.

The Electrical Resistance method has also been proven in practice that it can identify anomalous soil nails that are either short in length or have significant grout defects; but it is unable to discriminate between those two influences. In practice this may not be a detriment as both constitute a defect. The method can therefore be used as a simple technique for testing large numbers of soil nails, particularly as a blanket reconnaissance approach in the event that a total population of nails is tested. It also provides an inexpensive and quick way to gain further information that may help resolve anomalies shown by the TDR method (e.g. cases with no signal from nail end due to damaged wire or inverted reflection due to electrical contact between wire and nail bar).

The Sonic Impulse Method is not always successful and the waveform is not repeatable. This is the main drawback and the method is not considered usable in its present form. The Sonic Impulse and SW-TDR methods are not proven standard techniques but are considered to have the potential for further development given the possible advantage of these methods that existing soil nails without the provision of pre-installed wires or access tubes within grout sleeves could also be measured. Further work is needed to develop their potential for application.

It does appear that the potential of several other methods may not have been fully explored by their designers and that further directed development may be warranted. For example:

The Mise-a-la-Masse method could readily adopt the equipment (and set-up) used for resistance measurements and adopt a simple diagnostic measurement to discriminate certain types of grout deficiency in anomalous nails. The method could be deployed simultaneously with the Electrical Resistance method to provide further investigation of the anomalous soil nails.

The Electromagnetic Induction Method appears to yield the most accurate results for the determination of the bar length. In its present form, the Electromagnetic Induction method is not acceptable due to the requirement to implant two tubes within the grout sleeve.

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However, the system could be developed as a single coil system or as a spaced transmitter and receiver coil within a single plastic tube - to simplify the method and minimise practical constraints. In this respect the Electromagnetic Induction method could have the potential for routine application and there is possibility that it may also offer a reliable measure of grout integrity.

The proximity of the tube to the bar is the key to the electromagnetic result and therefore by using the same provision of a single tube within the grout, a miniature magnetometer could also be readily developed to provide absolute confirmation of the bar end, obviating the need for a separate borehole. Thus at close proximity to the bar, the Vector Magnetic method could also provide a direct and unequivocal indication of the bar end without ambiguity from adjacent soil nails or influence by the grout. In its present form, the Vector Magnetic method can only determine the length of shorter soil nails but the cost associated with the requirement of a separate borehole precludes its application on a regular basis.

It should be noted that the above potential modifications to the original methods have not been tested and appraised in a field application.

The findings from the assessments of the seven NDT methods at their present forms as summarised in this section are generally consistent with the conclusions and recommendations provided by GEO in their trials and studies conducted on the same NDT techniques, which are documented in GEO Report No. 133 (Cheung, 2003) and GEO Report No. 176 (Cheung & Lo, 2005).

3. REVIEW AND APPRAISAL OF TEST DATA

3.1 TDR Test Data from Trial Use of TDR on LPM Sites

3.1.1 General

Three sets of TDR test data have been provided by GEO from the trial use of the TDR method as a supplementary measure for quality control of soil nailing works at the LPM slope works sites.

The first set of data contains the initial TDR tests (over 700 no. tests) that were used for developing the reliability and uncertainty of the TDR tests. These soil nails were constructed in the normal manner and their lengths were physically measured. In addition to the raw data a database table has been provided that contains:

(i) Basic project details of soil nails tested;

(ii) TDR tests on controlled nails used for calibration;

(iii) Interpreted results of TDR tests including deduced lengths and as-built lengths of the soil nails tested; and

(iv) Pulse widths (if recorded) of TDR tests on the working and calibration nails.

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The second set contains the results of 4,710 TDR tests (including calibration tests) carried out by the testing contractors of the Public Works Central Laboratory (PWCL). A similar database table has been provided for the tests in addition to the raw data.

The third set of TDR test data contains the results of 1,224 TDR tests (including calibration tests) carried out by the Standard & Testing (S&T) Division and District Divisions of GEO. The corresponding database contains similar test data to that of the TDR tests conducted by PWCL.

The second and third sets of TDR data have been combined (and collectively called the routine TDR tests) and the data fields made consistent for statistical analysis. The first set of data (containing test results of soil nails with known lengths - controlled TDR tests) has been analysed separately.

3.1.2 Statistical Analysis of Initial Controlled TDR Tests Conducted on LPM Sites

At the outset of the statistical analyses of TDR tests conducted on the LPM sites, the variation of pulse propagation velocity among the nails of known length (i.e. the initial ~700 controlled tests) has been evaluated separately from the later routine test data for which the confidence in the physical measurement of the nail length is lower. For the controlled nails on each site, the measured pulse propagation velocity should be mainly a function of grout integrity as the length is known. The distribution of the pulse propagation velocity on each site is summarised in Table 2.

As shown in Table 2, these 700 test nails were spread over 10 sites. A total of 10 values of coefficient of variance (c.o.v.) have been used to estimate the variability of pulse propagation velocity on a single site. The c.o.v. can be modelled as a random variable the mean and standard deviation of which are determined to be 4.03% and 1.13% respectively. If a normal distribution model is used, there is a 95% confidence level that the c.o.v. will not exceed 5.88%. The 95% confidence level that the variability in the pulse propagation velocity falls within ±5.88% from its mean value include the uncertainty due to human judgement in data picking (identification of positions where the reflected pulses corresponding respectively to the clips of the test lead and the end of the test nail start to rise), the built-in error of the testing instrument and the variability of the grout integrity of the test nails.

The above should not be taken as the overall uncertainty of the TDR method for length measurement because under the existing testing regime the estimated length of a test nail is based on the pulse propagation velocity determined from a calibration nail instead of the mean velocity determined from all TDR tests undertaken on a site. The integrity of the grout sleeve of the calibration nail may not necessarily represent the average condition of the grout sleeves of the test nails. Hence, the difference in grout quality between the calibration nail and the ‘average’ nail would induce additional error in the length measurement using the TDR method. All of the above including the built-in error of the testing equipment and the uncertainties related to human judgement and variability in grout characteristics constitute the random errors that may occur in length measurement using the TDR method.

The error band of the initial ~700 nos. of controlled TDR tests has been re-evaluated (the previous assessment was undertaken by GEO and the results were reported in GEO

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Report No. 198 (GEO, 2006). The error is defined by the percentage difference in length estimation calculated by the following equation:

$$\text{(Estimated nail length - As-built nail length) / As-built nail length} \times 100\%$$

The frequency distribution of the length difference is presented in Figure 10(a). By fitting the probability distribution of the length difference with a normal model, as in Figure 10(b), the mean and standard deviation of the model are found to be 0.44% and 4.26% respectively, which are in basic agreement with the values reported in GEO Report No. 198 (Cheung, 2006). These values imply a 95% confidence level that the difference in length between the estimated value and as-built value due to overall uncertainty of the TDR test (including built-in error of testing instrument, human judgement, grout characteristics, reinforcement diameter and length etc) falls within -7.9% and +8.8%.

3.1.3 Statistical Analysis of Routine TDR Tests Conducted on LPM Sites

Following the above data analysis, separate statistical assessments have been carried out on the later routine TDR test data (total 5,777 nos. of test nails including 724 nos. of calibration nails) obtained from the LPM work sites to determine the variation between the measured nail lengths compared to the reported soil nail lengths. Five different cases have been considered to deduce nail lengths from the tests as follows:

(a) The average pulse propagation velocity determined from the calibration nail(s) identified for each batch of soil nails is used to deduce the lengths of that batch of test soil nails.

(b) The median pulse propagation velocity determined from the TDR test data obtained from each LPM site is used to deduce the lengths of test nails at that site.

(c) A single median pulse propagation velocity determined from all TDR test data from the LPM work sites is used to deduce the lengths of all test nails.

(d) A single mean pulse propagation velocity determined by averaging all TDR test data from the LPM work sites is used to deduce the lengths of all test nails.

(e) A single modal pulse propagation velocity determined from all TDR test data from the LPM work sites is used to deduce the lengths of all test nails.

These 5,777 test nails are spread over 525 different sites. The number of measurements is greater than 5,053 (5,777 minus 724 calibration nails) in Case (a) and is greater than 5,777 in Case (b) to Case (e) because some of the nails were tested more than once.

The frequency distribution of the length difference in each of Case (a) to Case (d) is presented in Figure 11(a), 12(a), 13(a) and 14(a) respectively. The data set is observed to fit

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a normal distribution in all cases. By fitting the probability distribution of the length difference with a normal model, as shown in Figures 11(b), 12(b), 13(b) and 14(b) for each of Case (a) to Case (d), the mean and standard deviation of the model are calculated and summarised in Table 3 for all cases considered.

It should be noted that the determination of modal velocity in Case (e) is not unanimous and is dependent on the magnitude of the interval range that is adopted in determining the average velocity of the highest frequency. Figure 15(a) and 15(b) show how different modal velocities could be derived from the data set when different interval ranges are considered. Two values of modal velocity are considered in the analysis undertaken for Case (e) as presented in Table 3.

In order to understand the distribution of the majority of the test data, the extreme outliers have been taken out from the data set in each of the above cases. The criteria used to delineate outliers are described as follows. The extreme outliers are defined as data values that lie above Q3 + 3 × IQR or below Q1 - 3 × IQR,

where Q1 = lower quartile of the data,
Q3 = upper quartile of the data, and
IQR = inter-quartile range (difference between Q1 and Q3).

The positions of Q1 and Q3 are (n+1)/4 and 3 × (n+1)/4 respectively where n is the original sample size.

Without excluding the extreme outliers, as shown in the frequency plots in Figures 11(a), 12(a), 13(a) and 14(a), the normal distribution will not be able to represent the data set well enough.

The range of percentage length difference at 95% confidence level results in Case (a) as shown in Figure 11(b) for the routine TDR data set has increased quite significantly when compared to the error band of the initial 700 controlled tests. In both Case (a) of the routine TDR data set and the initial data set of the 700 controlled tests, the length of each test nail was estimated based on an average pulse propagation velocity determined from a nail of known length (calibration nail). In is considered that since the uncertainty due to human judgement is unlikely to be significantly different between the two data sets as a standard procedure for testing and guidelines on result interpretation was followed, the increase of the error band of the routine TDR data set was considered to mainly due to the effect of greater variability in the grout characteristics of the test nails.

In Case (b) for the routine TDR data set, by adopting the median velocity determined from the TDR test data obtained from each LPM site as the reference pulse propagation velocity to deduce the lengths of test nails at that site, the range of percentage length difference at 95% confidence level is found to be reduced significantly when compared to Case (a). The mean difference is shifted to the positive side by almost 1% (from -0.98% to -0.11%). Hence, it seems by adopting the median velocity at each site to deduce the lengths of test nails at that site, the systematic error induced through the method by which the calibration nail is selected (where one may tend to select a calibration nail that has above average grout quality among the nails within a site) is reduced.

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In Cases (c) to (e), where a single median, mean or mode velocity determined from all TDR test data from the LPM work sites is used to deduce the lengths of all test nails, the percentage length difference ranges at 95% confidence level are found to be greater than that in both Case (a) and Case (b). The increase is considered to be largely due to the different wire types used at different sites, the effect of which was eliminated in Case (a) through using the same type of wire in both the calibration and test nails and was largely eliminated in Case (b) through using same type of wire on each site in general. Further, due to the use of a single velocity of all data, the effect of variability of grout characteristics among nails resulted from variable ground conditions at the different sites is not controlled or reduced, hence adding to a larger band of percentage difference in length measurement by TDR. In view of the results obtained in Cases (c) to (e), the use of a single mean velocity to deduce the lengths of all test nails is not likely to be feasible unless the wire type is standardised for use at all sites.

Based on the results presented above, the use of the median velocity measured at a site in lieu of the velocity determined from a calibration nail seems to provide more accurate results for the purpose of length measurement by TDR. However, it is possible that if more than 50% of the test nails are actually shorter than their reported lengths or if the contractor builds every nail short, then the resulted median velocity would be biased towards the high side and as a result the TDR tests could overestimate the lengths of the test nails collectively. This scenario is nonetheless considered to be highly unusual because the contractor will only need to be found negligent once to be liable. The options with regard to the method to be used to determine the reference propagation velocity will be discussed in Section 5.2.

3.1.4 Review of Sources of Uncertainties Associated with the TDR Method

Various sources of uncertainties in nail length estimation using the TDR method were identified by GEO (Cheung, 2006) as follows:

(a) Built-in error of testing instrument;

(b) Human judgement associated data picking;

(c) Wire type;

(d) Age of grout;

(e) Grout integrity (e.g. void in cement grout and void content);

(f) Steel bar diameter and length;

(g) Presence of bar coupler; and

(h) Wire configuration.

Based on the information provided in the available test data, the uncertainties in length estimation due to steel bar length and wire type have been investigated. The variation of pulse propagation velocity with steel bar length and wire cross-sectional area is presented in

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Figure 16(a) and 16(b) respectively. Trends of the velocity varying with bar length and wire diameter are observed but these trends are considered not significant within the overall variation of the results.

3.2 Grout Defects Investigation Using the TDR Method

Anomalies in the grout will cause ripples or partial reflections in the response signal due to the induced changes in the electrical impedance. In one of the special investigations undertaken by GEO, controlled TDR tests were conducted on soil nails with artificial grout defects to investigate the effect of grout loss at different locations. From these tests, it was found that grout loss in large size and at nail end could result in a superposition waveform and small grout loss at nail end cannot be detected (Figure 17). The approximate location of grout loss in the middle portion of a soil nail could be observed in the waveform (Figure 18). However, the amplitude of the waveform does not reflect the actual size of the grout loss. In most cases, significant noise was recorded at the initial part of the TDR waveform which precluded detection of grout defects near the top of the test nail. Grout loss in air could lead to apparently shorter soil nails. On the other hand, grout loss in water could theoretically lead to apparently longer soil nails.

3.3 Improvement of TDR Method

3.3.1 Use of Grout Pipes with Embedded Copper Wires

In one of GEO's special investigations, the use of grout pipes with embedded wires to replace the external wire for TDR testing has been investigated by GEO. Two types of this kind of grout tube have been used, namely Type A and Type B, as shown in Figure 19(a) and 20(a). Two 1 mm diameter copper wires are embedded in the Type A grout tube and two 0.5 mm diameter copper wires are embedded in the Type B grout tube. A total of 229 soil nails at two LPM sites have been tested with the Type A wires together with the normal wires and a total of 175 soil nails at three sites have been tested with the Type B wires together with the normal wires.

3.3.2 Statistical Analysis of Controlled Tests Using Grout Pipes with Embedded Wires

A summary of the success rates for measuring signal in the copper wires which are embedded in grout pipes is given in Table 4. As shown in Table 4, the success rate for measuring signal in both wires embedded in a grout pipe is slightly greater than 95% and the probability of receiving no signal from both wires is less than 1% which is similar to that when the normal external wire is used.

The variation of the pulse propagation velocity measured using these grout pipe embedded wires and the normal external wires are summarised and compared in Table 5. As shown in Table 5, the c.o.v. for the measurements taken at either one wire in the grout pipe is up to 4.9% and 11.3% for the Type A and Type B grout pipes respectively. However, if the average value of the measurements taken at both wires is used, the variation is reduced to 3.5% and 6.3% for the Type A and Type B grout pipes respectively, which is less than the variation of the measurements taken at the normal sensor wires. The frequency distributions

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of the pulse propagation velocity for the wires embedded in the Type A and Type B grout pipes in comparison with that for the normal external sensor wires are presented in Figure 19(b) and Figure 20(b) respectively. A schematic diagram showing the configuration of these wires along the test soil nail is also shown in each of the above figures.

It should be noted that the average pulse propagation velocity measured using the grout pipe embedded wires is almost 40% faster than the average velocity measured using the normal external wires. The significant change in velocity is considered to be largely due to the effect of the different plastic insulations of the wires on the overall dielectric property of the materials in close proximity to the conductor pair (i.e. wire and nail bar).

Also shown in Table 5 are the results of error in length estimation by use of two different methods for the determination of the reference propagation velocity as follows:

(a) The median pulse propagation velocity determined from the test data obtained from each site is used to deduce the lengths of test nails at that site.

(b) A single pulse propagation velocity determined by averaging all test data is used to deduce the lengths of all test nails.

It should be noted from the results that the error bands resulted from the above two cases are very similar, indicating that by standardising the type of wire to be used on all sites, a single pulse propagation velocity may be used to estimate the lengths of all test nails without the need for calibration nail(s) or the use of a median velocity.

4. FRAMEWORK FOR APPLICATION OF NDT TECHNIQUES

4.1 General Aims and Key Components

The existing quality assurance framework (interim) requires at least 2% with a minimum of 5 nails to be tested by TDR at each of the GEO LPM sites. For the private sector, on completion of installation of soil nails, the key supervision records will be submitted to the Building Authority (BA). Upon review of the supervision records, if the BA considers that there is cause for concern in relation to the quality of soil nailing works, the BA will require NDT of at least 1% of soil nails with a minimum of 2 nails per slope to verify the length of the installed soil nails.

Factors that could lead to problems in quality include:

(a) variable ground conditions and poor workmanship, and

(b) deliberate act of deception.

Currently TDR is the standard form of test deployed to check soil nail length. As such it applies particularly to the deterrence and detection of deliberate installation defects. The present sampling strategy of selecting a small number of soil nails in a random or semi-systematic manner may be adequate as a measure of deterrence to a deliberate act of

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deception. However, if the percentage of defective nails is small, it is highly unlikely that the sampling can detect soil nails affected by the above factors. Particularly, if a NDT technique is to be extended to grout integrity assessment, the existing small sampling scheme is likely to be inadequate. Hence, the sampling strategy and associated remedial action needs to be examined.

Furthermore, if other NDT techniques are to be considered for use in lieu of the TDR method, it is considered that the acceptance requirements should be rationalised for consideration by technique developers and NDT users.

For the above reasons, a framework for the application of NDT techniques in general for quality control of soil nailing works has been formulated in this study to be in line with the general objectives of the NDT to provide some assurance of the integrity of the soil nails installed. However, NDT is not recommended to be used as compliance testing. A major reason is that proof for poor construction method that is beyond doubt when condemning a defective work is difficult if not impossible. On the other hand, it is apparent from consultations held with the industry stakeholders that most people still have reservations over the reliability of NDT methods. As such, it is considered premature to implement the NDT tests as a compliance test under the proposed framework. There is a concern that if the NDT tests are used as compliance tests, all follow-up actions would have to be made contractual and that would require every party to buy in to the test being reliable.

The key components of the general framework for the application of NDT techniques in quality control of soil nailing works are categorised into two streams as follows:

(i) Components to be considered in approving a NDT technique for use in quality control of soil nailing works and these include:

   (a) Property to be measured;

   (b) Primary requirements for acceptance as a quality assurance tool;

   (c) Accuracy; and

   (d) Reliability.

(ii) Components for implementation of a NDT programme for quality control of soil nailing works and these include:

   (a) Sampling strategy;

   (b) Alert criterion that triggers follow-up action; and

   (c) Follow-up strategy including necessary contractual provisions.

A flowchart is provided in Figure 21(a) to illustrate the essential steps to be undertaken for each proposed NDT technique for satisfying the above framework components for application in the quality control of soil nailing works.

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4.2 Property to be Measured

The property of the soil nails to be measured using a NDT technique (i.e. objective of the test) needs to be well-defined in order to be considered for general use in quality control of soil nailing works. In proposing a NDT technique for use in quality control of soil nailing works, the property of the soil nail to be measured using the technique should be clearly defined to the vetting authority for their consideration in approving the technique.

The common objective should either be to evaluate the length of the soil nail steel bar or to assess the integrity of the grout annulus. If the test result of a NDT technique are dependent on more than one quality of the soil nail to be tested, consideration should be given to focusing on measuring one quality at a time and the testing procedure may need to be different for different objectives of the test in order to achieve optimal reliability in the measurement of a single quality of the soil nail under test. Alternatively, if a NDT technique does respond to the soil nail bar length and also to the integrity of grout but is unable to discriminate between the two influences, consideration may be given to supplement the technique with another one if defect discrimination is desired.

While the ability of most NDT techniques in the quantitative assessment of the grout integrity of soil nails has not been reliably proven, the primary and compulsory requirement for a proposed NDT technique for application in quality control of soil nailing works is at present in the measurement of nail bar length. The ability of a NDT technique to assess grout quality is an advantage but is not deemed essential at this stage.

4.3 Primary Requirements for Acceptance as a Quality Assurance Tool

Before a NDT technique is accepted for general use, the basic requirement would be to have a known consistent basis for interpretation, which shall be well documented and made available to users. Further, the provided basis for interpretation shall be applicable to most cases in the same manner and applied by most informed users in the same way. Only in this way, the parties whom the NDT results are concerned can have a common basis and understanding for discussion and/or appeal where it is considered justifiable. A method where the basis for interpretation is not well documented would be more suitable for special cases than for general use. The derivation of the NDT method shall also be based on sound scientific theories. A NDT method that is not founded on sound scientific theories is likely to be heavily relied on individual experience. Hence, the interpretation of this kind of NDT technique is generally less consistent as it is influenced by personal judgment. A NDT result that is known to have been based on individual experience and judgment would be subject to dispute, hence rendering the NDT technique ineffective in achieving its intended purpose. The above primary requirements for acceptance for a NDT technique for use in quality control of soil nailing works have been set out by GEO in the Technical Guidance Note No. 18 (TGN 18).

4.4 Accuracy

The accuracy of a NDT technique for measuring soil nail length is defined as the closeness of agreement between the NDT result and the true length of the nail. According to

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the definition in BS ISO 5725-1:1994, the term accuracy, when applied to a set of test results, involves a combination of random components collectively termed "precision" and a common systematic error or bias component which is a measure of "trueness". The random components or "precision" depends only on the distribution of random errors under the stipulated conditions. The repeatability and reproducibility conditions are particular sets of extreme conditions.

Under the proposed framework, before a NDT technique which provides a direct measurement is accepted for use, its accuracy in measuring a property of the soil nail shall be determined by carrying out a sufficient amount of controlled tests on soil nails of known properties in accordance with a recognised international standard such as BS ISO 5725. The technique developer should properly document the results of the controlled tests in accordance with the appropriate international standard and present it to the client when requested.

For any NDT method which operates in a comparative mode (e.g. the Electrical Resistance Method), its sensitivity in detecting defect of any one property of soil nail shall equally be determined with a sufficient amount of controlled tests.

For all NDT methods, the controlled tests for determination of accuracy or sensitivity (in the case of comparative methods) shall be carried out in the field on soil nails that are constructed in the normal manner as it is recognised that the results of most NDT techniques are subject either to disturbing influences along the length of the soil nail or to variable ground conditions. For NDT methods that are subject to influence of the surrounding ground, it is recommended that the controlled tests for determination of accuracy/sensitivity should be carried out under the variety of ground conditions which are likely to be encountered in the slopes of Hong Kong.

The factors/conditions that could exist which may affect the method's ability to perform at its optimal level should be identified and made known to the potential users.

4.5 Reliability

The reliability of a NDT technique has to do with the consistency of the measurements. There are several general classes of reliability estimates, of which the following two are considered to be most relevant to NDT techniques:

(a) Inter-observer reliability - used to assess the degree to which different observers/operators give consistent estimates of the same phenomenon;

(b) Test-retest reliability - used to assess the consistency of a measure from one time to another.

It is expected that, before a NDT technique is accepted for use in quality verification of installed soil nails, its reliability in the form of both the above-mentioned reliability types should be demonstrated through trial tests carried out on actual installed soil nails constructed in the normal manner. Tests used to demonstrate reliability of a NDT technique in

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measuring a property of soil nail installed in the field to the claimed accuracy may be covered under the same programme of controlled tests for determination of accuracy.

4.6 Sampling Strategy

4.6.1 General

For NDT techniques which provide direct measurement of the properties of installed soil nails, the option of conducting full tests on all nails is normally not practicable and is generally not preferred by both the Employer and Contractor for the reasons of additional incurred cost and time. Sampling can be designed to provide a reasonable quality assurance that meets the targeted objective associated with an acceptable consumer's risk. However, it is fundamental that some defective products (soil nails) may be accepted if sampling is adopted. As discussed in Section 4.1, the existing sampling strategy is considered to be too small to be able to detect defective nails if the percentage of defective nails is not large. Hence, for NDT techniques, which provide direct measurement of the properties of installed soil nails, it is proposed to adopt a sampling strategy based on the procedures documented in the BS 6001-1 (ISO 2859-1) (BSI, 1999).

Under the proposed sampling plan, each item sampled must be judged as either conforming or non-conforming with respect to a specified requirement. As NDT is not recommended as a compliance test, the batch (termed "lot" in BS 6001) will be determined as whether the number of non-conforming items identified in the batch exceeds an "alert criterion" where follow-up action is warranted. The sampling procedures should be designed to provide an acceptable quality limit to the employer such that majority of substandard lots are rejected.

The proposed sampling and lot rejection rules are set to achieve 90% confidence in rejecting a "lot" with more than 20% non-conforming soil nails. It should be noted that the proposed sampling strategy to be discussed in Section 4.6 and the associated follow-up strategy in Section 4.8 are applicable only to NDT tests that are carried out on individual nails to give an inferred measurement of a soil nail property. For NDT techniques that derive results in a comparative mode such as the Electrical Resistance method, the sampling strategy is not suitable. The sampling and follow-up strategy for comparative NDT techniques are discussed separately in Section 4.10.

4.6.2 Formation of Lots

The soil nails to be constructed on a site shall be assembled into identifiable lots. Each lot shall, as far as is practicable, consist of soil nails of a single type, size and composition, constructed under uniform conditions at essentially the same time (period). The formation of lots and the associated lot size shall be identified by the Contractor for approval by the Engineer. The Contractor should be given as much flexibility as considered reasonable to define the lots to suit his construction sequence providing the above rules are complied in general.

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4.6.3 Determination of Minimum Sample Size and Acceptability of Lots

The required sample size for a given lot of installed soil nails is dependent on the particular lot size. Table 6 (based upon Table 1 of BS 6001-1 (BSI, 1999)) shall be used to obtain the appropriate sample size for a particular lot size.

A sampling plan is a combination of sample size to be used and the associated alert criterion. The number of soil nails to be tested by the approved NDT technique shall be equal to the sample size given by the plan. If the number of non-conforming soil nails found in the sample is equal to or less than the alert criterion, no further investigation is considered necessary for the lot. If the number of non-conforming soil nails is greater than the alert criterion, follow-up action is warranted.

It should be noted from Table 6 that the minimum sample size does not increase in a direct proportional manner with the increase in the lot size. If the soil nails on a site are being divided into more lots for testing, the soil nails could be tested at the earliest opportunity and hence decision as whether follow-up action is needed can also be made earlier. The potential problems associated with the difficulties in providing access and work platform for NDT testing at completion of the soil nailing works may be alleviated. However, lots with small number of soil nails will increase the cost of mobilising the testing contractor and is not preferable. A general lot size of more than 50 nails should be maintained as far as practicable.

The soil nails to be tested within each identified lot shall be selected by the Engineer. The follow-up strategy to be adopted for lots exceeding the alert criterion will be discussed in detail in Section 4.8.

4.6.4 Consumer's Risk

The sampling schemes provided in BS 6001-1 (BSI, 1999) are intended to be used primarily for a continuing series of lots, that is, a series long enough to allow switching rules to be applied. These rules provide a protection to the Employer by means of a switch to tightened inspection (with tightened lot acceptability criteria) should a deterioration in quality be detected. For the case of soil nail construction particularly for small sites, the series of lots may not be long enough to allow the switching rules to be applied. For this reason, it is proposed to limit the selection of sampling plans to those that give consumer's risk quality not more than a specified limiting quality protection. Sampling plans for this purpose can be selected by choosing a consumer's risk quality (CRQ) and a consumer's risk (probability of acceptance) to be associated with it.

A consumer's risk quality of 20% non-conforming soil nails with an associated probability of acceptance of 10% or less is recommended to be adopted for individual lots under the proposed sampling framework. In order words, it is aimed to achieve 90% confidence in not accepting a "lot" with more than 20% non-conforming soil nails. Table 7 assembles the sampling plans provided in BS 6001-1 for different lot sizes that guarantee a consumer's risk quality (CRQ) of 20% non-conforming soil nails for a consumer's risk of 10%. Hence, for example, for a lot size of 100 soil nails, the minimum sample size should be 20 and the acceptance and non-acceptance numbers should be 1 and 2 respectively

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(Table 7). It should be noted from Table 7 that for a CRQ of 20% the minimum number of soil nails to be tested in any "lot" is 10.

The proposed customer's risk quality is chosen to strike a balance between the testing frequency (i.e. additional cost and time) and the desired minimum quality level. In other works, if a higher quality limit is desired, the testing frequency (sampling rate) will have to be increased.

4.7 Non-conforming Threshold

Under the proposed framework for the application of NDT techniques in general for quality control of soil nailing works, the soil nail must be judged as conforming or non-conforming. The non-conforming threshold is defined as the point below which anomalous result in the NDT measurement indicates that the soil nail falls short of the required construction specifications.

A soil nail found to be non-conforming based on the result of a non-destructive test is deemed to have non-conformities associated with the properties to be measured. For example, in TDR tests with pre-installed wires, the non-conformities relates to the quality of the grout annulus and the length of steel bar. When defining the non-conforming threshold for each of the NDT techniques suitable for use in quality control of soil nailing works, its impact on giving false alarm should be considered.

The non-conforming threshold for different NDT techniques are expected to be different, which are inevitably related either to the overall uncertainty of the NDT tests in deducing the length of the soil nail steel bar or to the probable maximum influence of variable ground conditions such as a step in rockhead as in the case for the Electrical Resistance Method.

While there are few targeted site tests carried out on normally constructed soil nails to investigate the effects of natural grout defects of various magnitudes on the test results of NDT methods, it is still uncertain how grout defects may affect the test results. Hence, the non-conforming threshold for NDT tests that are influenced by grout quality must be set prudently to avoid giving unnecessary false alarm.

4.8 Follow-up Strategy

Under the sampling procedure recommended in the framework, the testing for a lot of soil nails shall be terminated when the non-conforming nails does not exceed the alert criterion. However, the Employer shall have the right not to accept any soil nail found non-conforming during the testing.

For a lot found to have non-conforming nails exceeding the alert criterion based on result of the initial single sampling plan, subject to approval by the Engineer, the Contractor may step up to the single sampling plan one level higher with its corresponding larger sample size (~50% more). If the results from both single sampling plans indicate the number of non-conforming nails still exceed the alert criterion, all untested nails within the lot shall be tested.

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In such case, a design review should be carried out by the Engineer. Additional investigation by means of other NDT techniques or other methods could be required at this stage. Following the design review, and additional investigation if conducted, the Engineer will decide in consultation with the Employer on whether additional soil nails will be constructed. The Contractor will be required to install additional nails upon receiving instruction from the Engineer. The decision from the Engineer on whether additional nails need to be installed may be deferred to when the test results of the last lot of soil nails at a site are obtained.

4.9 Contractual Provisions

All NDT tests are to be carried out by an independent testing contractor and paid by the Employer. However, the Contractor shall provide the necessary safe access and work platform for all NDT tests and accommodate in the construction programme the time for conducting the tests. Further investigation and remedial works will be paid by Contractor only if it is proved that the anomaly is caused by defective construction (e.g. short nail or poor grouting practice). Otherwise, all costs will be borne by the Employer.

4.10 Sampling and Follow-up Strategy for Comparative NDT Techniques

For comparative NDT techniques such as the Electrical Resistance Method, the tests are usually rapid and the cost per test is low compared to the mobilisation and setting-up costs. Hence, for NDT techniques which operate in a comparative mode, it is recommended to test all soil nails installed on a site. Following the tests, a design review if considered necessary by the Engineer should be carried out based on the results of all tests. A decision will be made based on the design review whether or not certain nails need to be replaced. The contractual provisions for the use of these techniques should be the same as those recommended for the techniques of direct measurement.

5. APPLICATION OF FRAMEWORK TO TDR TESTING

5.1 Accuracy and Reliability of the TDR Method

The precision of the TDR method under the repeatability and reproducibility conditions has been assessed by GEO through considering the single-operator and multi-operator uncertainties. The findings of the assessment are reported in GEO Report No 198 (GEO, 2006). Random errors that occur in TDR testing for determining soil nail length may also be related to the difference in the amount of grout defects present in the calibration nail and the test nail. The method by which the calibration nail is selected may induce systematic error in length measurement using the TDR method if one tends to select a calibration nail that has above average grout quality among the nails within a site.

The parameter used to evaluate the accuracy of the TDR method for nail length measurement is the total error of each of the TDR tests recorded in the TDR data sets and is defined as the percentage variation between the measured nail length compared to the reported soil nail length (length difference). By fitting the probability distribution of the length difference with a normal model, the mean and standard deviation of the accuracy

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model for the TDR method have been determined in Section 3. Using these values, the level of confidence that the percentage error on length estimation using the TDR method falls within a certain range, has been established.

The reliability of the TDR method for nail length measurement has been estimated by GEO through the multi-operator tests (i.e. inter-observer reliability) and single-operator tests (i.e. test-retest reliability over short time interval) in accordance with BS 6001. The results are reported in GEO Report No. 198 (GEO, 2006).

Based on the findings from the accuracy and reliability tests (the initial 700 controlled tests) which were undertaken by GEO and the further statistical analyses carried out in this study on the routine TDR data set (5,777 test nails) for evaluation of the percentage length difference ranges at 95% probability distribution, it is considered that the accuracy and reliability of the TDR method in the evaluation of soil nail length have been sufficiently proven.

5.2 Review of Testing Regime

Consideration has been given to the testing regime that is commonly adopted on sites for TDR testing. For the TDR method the main drawbacks that have been experienced are as follows:

(a) Variable ground conditions may lead to difficulty in properly forming a grout sleeve around the soil nail, e.g. formation of voids around the steel bar, leading to variable dielectric constant (variable pulse velocity), even on individual sites and adjacent soil nails.

(b) Selective adoption of individual calibration nails may not be appropriate over large sites and may result in systematic error in length estimation.

(c) Method relies on assumed correct installation of the wire(s) and uniformity of wire insulation.

(d) Data analysis for length estimation is subject to systematic error caused by the influence of grout integrity on the pulse propagation velocity.

Due to the above it is not clear whether TDR is unequivocally measuring the length of the soil nail.

With regard to the use of calibration nails for determination of a reference velocity, these calibration soil nails are typically chosen on site at random (usually a long nail) for TDR testing, with guidance from the Resident Engineer or where the soil nail length has been observed directly at installation. There is no guarantee that the calibration nail is typical for all others or even is the correct length. It may therefore be better to consider the mean (or median) velocity for a group of soil nails.

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From the results of the statistical analyses presented in Section 3.1, it is shown that the use of the median velocity from each site seems to provide more accurate results for length measurement than the use of calibration nails. If the proposed single sampling strategy is used (i.e. minimum sample size becomes 10 for each batch of soil nails), the use of median velocity is feasible.

As the value of the median velocity has to be unbiased for achieving acceptable accuracy in the TDR test, it is proposed that the median velocity should be compared with the mean velocity value obtained from a minimum of three calibration nails with enhanced supervision at each site. Assuming a normal distribution for the pulse propagation velocity of all nails on a site, it is found based on the results of the 700 controlled nails on 10 sites that with 95% confidence the mean velocity of all soil nails on a site would be within ±15% of the mean velocity determined from three calibration nails. The critical stage of construction of these calibration nails should be observed by an engineer-grade supervisor. If the median velocity is more than 15% faster than the mean velocity value determined from the calibration nails, the mean velocity from the calibration nails should be used instead to estimate the lengths of the test nails.

An alternative option is to adopt the mean velocity determined from a minimum of three calibration nails on each site with enhanced site supervision described as above. This option, although less preferred in the way that it will in most cases result in a larger error band in terms of length measurement compared to the use of median velocity at each site, is considered to be more reliable than the existing testing regime.

5.3 Review of Non-conforming Threshold

In the existing framework for TDR, a 15% variation in the deduced length is used as a threshold that identifies soil nails with abnormal TDR test results and may trigger further investigation. This variation, which relates to the overall uncertainty of the TDR tests in deducing the length of the soil nail steel bar, has effectively become the ‘non-conforming threshold’ for the TDR method. From the natural variance of TDR results as revealed by the two TDR data sets (the 700 controlled tests data set and the 5,777 routine tests data set), although there seems to be some room for tightening the non-conforming threshold for TDR, more thoughts are required before doing so for the reasons given below.

The variation in the deduced length may be attributed solely to the difference in grout integrity between the calibration nail and the test nail and so far very limited site tests on real soil nails have been performed to investigate the effects of natural grout defects of various magnitudes on the TDR test result. It may be possible that an acceptably small grout defect occurring at a couple of locations along the test nail could result in a TDR-deduced length that is more than 15% shorter than the design length considering also the effects due to other uncertainties related to human judgement and wire configurations and built-in error of testing equipment etc which add to the overall testing error. Rejecting and replacing soil nails with possibly negligible defects, resulted from tightening the non-conforming threshold, would be a waste of money and have unnecessary adverse impact on the programme.

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Furthermore, in terms of length estimation, allowing a 15% variation in the deduced length should not significantly affect the ability of TDR or any other kind of NDT test to deter deliberate act of deception.

5.4 Application of Framework to TDR Testing

As discussed in Section 5.1, the accuracy and reliability of the TDR method in the evaluation of soil nail length have been sufficiently proven. Furthermore, a standardised test procedure and a consistent basis for interpretation have been developed for the TDR method and are available to all users in the document "Guidelines on Test Procedure and Sample Test Results Using Time Domain Reflectometry (TDR) to Determine the Length of Installed Soil Nails" published by GEO. Hence, it is considered that the TDR method has already satisfied the key components for acceptance of a NDT technique under the general framework for the application of NDT techniques in the quality control of soil nailing works. The TDR method is therefore considered to be ready for application as a NDT technique for general use.

A flowchart is provided in Figure 21(b) to illustrate how the proposed sampling strategy and modified testing regime will be applied to TDR testing. As shown in the flowchart, the Contractor will first define the lots for approval by the Engineer. Upon approval by the Engineer, the minimum sample size for each lot will be determined according to its size in accordance with Table 8. After the minimum sample number is determined, the Engineer will then select the soil nails from each lot to be tested. The TDR tests will be carried out by a designated independent testing contractor who will deduce the travel time of the TDR pulse reflected from the inferred nail end of each test nail. The Engineer, based on the travel time obtained by the testing contractor, will calculate the average pulse propagation velocity for each test nail. From the tests carried out on each lot, the median velocity will be determined and used as the reference propagation velocity to estimate the length of each test nail (provided that the comparison with the mean velocity determined from three calibration nails is satisfactory) and gauge the acceptability of each test nail according to the non-conforming threshold of the TDR test. A test nail with inferred length more than 15% shorter than the reported length will be considered as non-conforming. Conversely, a test nail with inferred length longer than or less than 15% shorter than the reported length will be regarded as conforming.

An example of a mock-up site is then presented in Figures 22 to 25 to further demonstrate how the proposed testing framework (single sampling) could be followed in the case of TDR testing. The sample site has a total number of 200 soil nails and it is divided into three lots as shown in Figure 26. For Lot 1, which contains 75 soil nails (i.e. ≤ 90), the minimum sample number is 13 so as to achieve a customer's risk quality of not more than 20% non-conforming (Table 8). Out of the first 13 soil nails that are randomly selected to be tested, 1 non-conforming soil nail is detected. As the number of non-conforming soil nails exceeds the alert criterion of the initial sampling plan, 7 more nails are tested according to the second sampling plan. No non-conforming soil nail is detected among these 7 nails. Hence, the total number of non-conforming soil nails for Lot 1 is 1, which is equal to the alert criterion of the second sampling plan. No further investigation is considered necessary for Lot 1. However, action should be considered to rectify the non-conforming nails, e.g. by replacement of the nails. For Lot 2, 2 non-conforming soil nails are detected from the 10 nails tested. Since the number of non-conforming soil nails is already larger than the alert

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criterion of the next sampling plan, further investigation is required for Lot 2. All the remaining soil nails in Lot 2 are then tested and a design review is carried out based on the results of all tests. For Lot 3, again 13 soil nails are tested and none are identified to be non-conforming. Hence, no further investigation is needed for Lot 3 according to the sampling plan.

6. CONCLUSIONS

The available information and data on the use of the NDT techniques have been reviewed and appraised. Seven NDT techniques have been considered and each technique has been assessed in terms of its relative merits and limitations. Basically, it is found that no method can discriminate grout defects unambiguously. The inferred nail length from TDR is somewhat sensitive to the integrity of the grout sleeve. Voids within the grout sleeve will have an effect on the propagation velocity of the TDR pulse. However, the accuracy and reliability of the TDR method with a pre-installed wire to measure nail length have been proven in practice. This method is considered to be an effective method in detecting soil nails with significant defect in length and grout and the development of the technique has satisfied the proposed framework components for general use as a NDT technique.

The Electrical Resistance method has been proven in practice that it can identify anomalous soil nails that are either short in length or have significant grout defects but it is unable to discriminate between those two influences. In practice this may not be a detriment, as both constitute a defect. The method can therefore be used as a simple technique for testing large numbers of soil nails, particularly as a blanket reconnaissance approach in the event that all the nails are tested. It also provides an inexpensive and quick way to gain further information that may help resolve anomalies shown by the TDR method (e.g. cases with no signal from nail end due to damaged wire or inverted reflection due to electrical contact between wire and nail bar).

It appears that the potential of several other methods may not have been fully explored and that further directed development may be warranted. The Electromagnetic Induction method, for example, in its present form, is not ideal due to the requirement to implant two tubes within the grout sleeve. However, the system may be able to be developed as a single coil system or as a spaced transmitter and receiver coil within a single plastic tube - to simplify the method and minimise practical constraints. In this respect the Electromagnetic Induction method could supersede TDR in terms of accuracy and provide unequivocal results provided that the construction of the plastic tube is practical and acceptable. There is also the possibility that it may also offer a measure of grout integrity.

Similarly, by using the same provision of a single tube within the grout, the Vector Magnetic Method may be developed using miniature magnetometers to provide absolute confirmation of the bar end without ambiguity from adjacent soil nails or influence by the grout, obviating the need for a separate borehole. In its present form, the Vector Magnetic method can only determine the length of shorter soil nails but the cost associated with the requirement of a separate borehole precludes its application on a regular basis.

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The Mise-a-la-Masse method, that uses essentially the same equipment, could in-principle be carried out simultaneously with the Electrical Resistance method to augment the characterisation of anomalous soil nails.

The other two methods, the Sonic Impulse and Surface Wave Time Domain Reflectometry methods are not proven standard techniques but are considered to have potential for further development considering the possible advantage of these methods that existing soil nails without the provision of pre-installed wires or access tubes within grout sleeves could also be measured. At their present forms, both methods lack a consistent basis and procedure for interpretation which shall be available for all users. For the Sonic Impulse method, until a post-processing method is well established and found to be reliable on a wide range of situations this method cannot be considered for general use.

Since the commencement of the trial use of the TDR method with pre-installed wires at the LPM slope works sites in mid-2004, about 700 controlled TDR tests (on nails of known lengths) had been conducted by GEO and by the end of June 2006 a total of 5,777 soil nails at 525 LPM sites had been tested using the TDR method under the trial testing programme. Separate statistical assessments have been carried out on these two sets of data to determine the variation between the measured nail lengths compared to the reported soil nail lengths.

Based on these statistical assessments, it is found that the use of the median velocity measured at a site in lieu of the velocity determined from a calibration nail is likely to provide more accurate results for the purpose of length measurement by TDR. By adopting the median velocity determined from the TDR test data obtained from each LPM site as the reference pulse propagation velocity to deduce the lengths of test nails at that site, the range of percentage length difference between the estimated value and reported value falls within -8.8% and +8.6% at 95% confidence level if a normal distribution model is used.

The uncertainties in length estimation using TDR due to steel bar length and wire type have been investigated based on information provided in the available test data. Trends of the velocity varying with bar length and wire diameter are observed but these trends are considered not to be significant within the overall variation of the results. On the other hand, the accuracy of the TDR method depends on the proper installation and material consistency of the electric wire. If the pre-installed wire is damaged and in electrical contact with the steel bar (at a location other than the bar end), an early inverted wave reflection will be resulted with no reflection from the nail end.

With respect to grout defect investigation, anomalies in the grout will cause ripples or partial reflections in the TDR response signal due to the induced changes in the electrical impedance. From controlled TDR tests conducted on soil nails with artificial grout defects at different locations in one of the special investigations, it was found that a large amount of grout loss at the nail end could result in a superimposed waveform and a small grout loss at the nail end cannot be detected. The approximate location of grout loss in the middle portion of a soil nail could be observed in the waveform. However, the amplitude of the waveform does not reflect the actual size of the grout loss. Grout loss in air could lead to apparently shorter soil nails. On the other hand, grout loss in water could theoretically lead to apparently longer soil nails.

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In one of GEO's special investigations, the use of grout pipes with embedded wires (two in each pipe) to replace the external wire for TDR testing has been investigated. It was found that, while the pulse propagation velocity significantly increased over that of single wire system, the variation of the results was reduced. The coefficient of variance for the measurements taken at either one wire in the grout pipe is up to 4.9% and 11.3% respectively for the two types of grout pipes used. However, if the average value of the measurements taken at both wires is used, the variation is reduced to 3.5% and 6.3% respectively, which is less than the variation of the measurements taken at the normal external sensor wires. The use of embedded wires in grout pipe would diminish the possibilities of fiddling with the wire configurations and provide more reliable results.

A framework for the application of NDT techniques in general in quality control of soil nailing works has been formulated in this study to be in line with the general objective of providing some assurance of the integrity of the installed soil nails. The key components of the general framework comprise the components to be considered in approving a NDT technique for use in quality control of soil nailing works and the components for implementation of a NDT programme.

While the ability of most NDT techniques in the quantitative assessment of grout integrity of soil nails has not been reliably proven, the primary requirement for a proposed NDT technique for application in quality control of soil nailing works is the measurement of nail bar length. The ability of a NDT technique to assess grout quality is also an advantage.

Before a NDT technique is accepted for general use, it has to have a known consistent basis for interpretation, which shall be well documented and made available to users. This primary requirement for acceptance for a NDT technique has been explained in the Technical Guidance Note No. 18 (TGN 18).

Before a NDT technique which provides a direct measurement is accepted for use, its accuracy in measuring a property of the soil nail shall be determined by carrying out a sufficient amount of controlled tests on soil nails of known properties in accordance with a recognised international standard. For any NDT method which operates in a comparative mode, its sensitivity in detecting defect of any one property of soil nail shall, equally, be determined with a sufficient amount of controlled tests.

The reliability of a NDT technique, which has to do with the consistency of the measurements, should also be demonstrated through trial tests carried out on actual installed soil nails constructed in the normal manner before the technique is accepted for use in quality verification of installed soil nails.

Under the proposed framework for the application of NDT techniques in general for quality control of soil nailing works, the non-conforming threshold is defined as the point below which anomalous result in NDT measurement indicates that the soil nail falls short of the required construction specifications. The non-conforming threshold for different NDT techniques are expected to be different, and are inevitably related either to the overall uncertainty of the NDT tests in deducing the length of the soil nail steel bar or to the probable maximum influence of variable ground conditions such as a step in rockhead as in the case for the Electrical Resistance method. The non-conforming threshold for NDT tests that are influenced by grout quality must be set prudently to avoid giving unnecessary false alarm.

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In the existing framework for TDR, a 15% variation in the deduced length is used as a threshold that identifies soil nails with abnormal TDR test results and may trigger further investigation. This variation, which relates to the overall uncertainty of the TDR tests in deducing the length of the soil nail steel bar, has effectively become the non-conforming threshold for the TDR method. Although there seems to be some room for tightening this threshold for TDR, more thoughts are required before doing so because the variation in the deduced length may be attributed solely to the difference in grout integrity between the calibration nail and the test nail. Hence, tightening the non-conforming threshold could lead to rejecting and replacing soil nails with possibly negligible defects. This would be a waste of money and have unnecessary adverse impact on the programme. Furthermore, in terms of length estimation, allowing a 15% variation in the deduced length should not significantly affect the ability of TDR or any other kind of NDT test to deter deliberate acts of deception.

The present sampling strategy of selecting a small number of soil nails in a random manner that is adopted on both LPM and private soil nailing sites may be adequate as a measure of deterrence to a deliberate act of deception. However, if the percentage of defective nails is not very large, the existing sampling strategy is too small to be able to detect the defective nails. Hence, the sampling strategy and associated follow-up action have been examined in this study and it is proposed that a sampling strategy based on the procedures documented in the BS 6001-1 (ISO 2859-1) be adopted for NDT techniques which provide direct measurement of a property of installed soil nails. The proposed sampling and lot "alert criterion" are set to achieve an acceptable quality level of 4% for soil nails passing the sampling plan and a consumer's risk of having 90% confidence in rejecting a "lot" with more than 20% non-conforming soil nails. The proposed customer's risk quality is chosen to strike a balance between the testing frequency (i.e. additional cost and time) and the desired minimum quality level. In other works, if a higher quality limit is desired, the testing frequency (sampling rate) will have to be increased.

Regarding follow-up strategy, in case of the alert criterion being exceeded, all untested nails within the "lot" shall be tested and a design review should be carried out by the Engineer. Additional investigation by means of other NDT techniques or other methods could be required at this stage. Following the design review and additional investigation if conducted, the Engineer will decide in consultation with the Employer on whether additional soil nails will be installed.

In respect of contractual provisions, all NDT tests are to be carried out by an independent testing contractor and paid by the Employer. However, the Contractor shall provide the necessary safe access and work platform for all NDT tests. The Contractor shall also allow in the works programme the time for the testing. Further investigation and remedial works will be paid by Contractor only if it is proved that the anomaly is caused by defective construction (e.g. short nail or poor grouting practice). Otherwise, all costs will be borne by the Employer. Non-destructive tests are not yet recommended to be used as compliance tests because they do not provide proof of defective construction methods. Further, there is a concern that if the NDT tests are used as compliance tests, all follow-up actions would have to be made contractual and that would require every party to buy in to the test being reliable.

For NDT techniques which operate in a comparative mode, it is recommended to test all soil nails constructed on a site as the tests are rapid and the cost per test is low compared to

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the mobilisation and setting-up costs. Where anomalies are found from the tests, a design review should be carried out and a decision made on whether or not additional nails are required. The contractual provisions for the use of these techniques should be the same as those recommended for the techniques of direct measurement.

Based on the review undertaken in this study, the TDR method with preinstalled wires is considered to have satisfied the framework components including the requirements for proven accuracy, reliability and a consistent basis for interpretation in the evaluation of soil nail length. The method is therefore ready for general use as an audit tool in quality control of soil nailing works. For application of the proposed framework to TDR testing, consideration has been given to the testing regime that is commonly adopted on sites. If the proposed single sampling strategy is used, the use of median velocity is feasible and preferable to the use of calibration nails. As the value of the median velocity has to be unbiased for achieving acceptable accuracy in the TDR test, it is proposed that the median velocity should be compared with the mean velocity value obtained from a minimum of three calibration nails with enhanced supervision at each site. If the median velocity is more than 15% faster than the mean velocity value determined from the calibration nails, the mean velocity from the calibration nails should be used instead to estimate the lengths of the test nails. Alternatively, the reference pulse velocity value can be determined by taking the mean velocity from three calibration nails in each site.

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Table 1 - Limitations Table (Sheet 1 of 2)

		Electrical Resistance	Mise-a-la-Masse	Vector Magnetic	Electro-magnetic Induction	Sonic Impulse	Surface Wave TDR
TDR	Electric wire is required to be pre-installed along the length of soil nail bar	Direct electrical contact with the cleaned nail bar head is preferred	Direct electrical contact with the cleaned nail bar head is preferred	It requires a test drill hole to be prepared closely adjacent to soil nail and approx. 2 m longer than soil nail design length	Two open plastic tubes are required to be inserted with the grout at the time of soil nail installation	Acoustic impedance of soil nail is a function of combined elastic properties of steel bar and grout and will vary for variable grout conditions. Hence, the propagating impulse will be partially reflected by those variable conditions, adding spurious responses to recorded signal and diminishing onward propagating signal in both forward and return directions	Derived impedance train will include second order responses which should not be attributed to uniquely to individual grout defects
Practical Limitations	Accuracy depends on proper installation and material consistency of the electric wire			Uncertainty of test borehole alignment in relation to the installed soil nail under test may result in misleading magnetic results from adjacent soil nail	Pre-installed plastic tubes may have detrimental effect on grout integrity of soil nail	Impulse characteristics are not always repeatable due to the non-repeatability of the method of impulse generation	
				Magnetic properties of steel bar appears to be at or near saturation level, hence magnetic induction with reversal to discriminate soil nail under test is only moderately successful	Careful control has to be ensured to admit and maintain the coils together in the survey	Signal attenuation would occur progressively due to normal energy absorption and lateral refraction loss into containing ground	

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Table 1 - Limitations Table (Sheet 2 of 2)

		Electrical Resistance	Mise-a-la-Masse	Vector Magnetic	Electro-magnetic Induction	Sonic Impulse	Surface Wave TDR
TDR	Results would be affected by grout integrity, hence not able to determine nail length unequivocally	Method cannot discriminate between a bar deficiency and a grout deficiency	Method is directly subject to influence of variable ground conditions as well as to nail characteristics, which renders accuracy of length evaluation unacceptable	Due to dominant magnetic polarization of bar may not occur at bar end, special software is needed for processing of combined magnetic vector profiles to enhance weak secondary polarization sufficiently to observe the nail end condition	Method in its present form is not sensitive to grout defects	Method in its present form is not sensitive to grout defects	Results would be affected by grout integrity, hence not able to determine nail length unequivocally
Theoretical Limitations	Interpretation of waveform in terms of grout integrity is largely qualitative	Sensitivity to deficiencies decreases with increasing soil nail length	Results would be affected by adjacent nails	Method in its present form is not sensitive to grout defects		Accuracy of measurements on longer soil nails diminishes by stretching the reflected primary impulse into a signal 'train'	Interpretation of waveform in terms of grout integrity is largely qualitative
	Current practice requires site calibration to determine the reference propagation velocity	As a comparative method, it must rely upon a statistical measure to provide a datum for evaluating the significance of the results				Method is subject to determination of a calibration velocity with resultant scope for significant error	Calibration velocity is needed but would induce uncertainties on assumption of uniformity
Equipment Limitations				Equipment is not commonly available and costs are relatively high compared with the equipment of other NDT techniques	Equipment is not commercially available at present	Characteristics of the available input and gain filters may be an issue considering the short travel times	Equipment is not commercially available at present and the prototype equipment used in HK is proprietary and no details have been released

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Table 2 - Variation of Pulse Propagation Velocity among Nails of Known Length (Initial Controlled Tests)

Site Location	No. of Nails (Tests)	Min Velocity (m/ns)	Max Velocity (m/ns)	Mean Velocity, μ (m/ns)	Standard Deviation, σ (m/ns)	Coefficient of Variation, (σ/μ) COV (%)
6NW-C/C209	24	0.0625	0.0755	0.0698	0.0041	5.87%
6SW-A/CR253	21	0.0648	0.0765	0.0702	0.0032	4.58%
7NE-C/C113	45	0.0833	0.1016	0.0896	0.0036	4.00%
7NW-B/CR426	19	0.0828	0.0905	0.0862	0.0023	2.72%
7SW-C/C100	46	0.0764	0.0855	0.0806	0.0024	2.96%
7SW-D/C167	246	0.0716	0.0917	0.0792	0.0031	3.86%
8NW-C/C97	120	0.0833	0.1018	0.0923	0.0038	4.11%
11NW-D/C92	6	0.0800	0.0931	0.0877	0.0047	5.37%
11SE-D/C57& 11SE-D/C247	31	0.0881	0.1014	0.0949	0.0043	4.49%
Natural Slope	146	0.0693	0.0787	0.0735	0.0017	2.31%
Total No.	704		Mean	0.0824	μ of COV	4.03%
			Min	0.0698	σ of COV	1.13%
			Max	0.0949	95% confidence	$\leq$ 5.88%

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Table 3 - Summary of Distribution Parameters for the Routine TDR Data Set

Case	Method of Determination of Reference Pulse Propagation Velocity	No. of Tests	No. of Outliers	Max –ve diff (%)	Max +ve diff (%)	Mean Diff (%)	Standard Deviation (%)	Length Difference at 95% Confidence Level (%)
(a)	Calibration nail	5155	70	-26.72	+24.84	-0.98	5.83	-12.4 to +10.4
(b)	Median velocity at each site	5890	96	-17.68	+14.24	-0.11	4.44	-8.8 to +8.6
(c)	Single median velocity (0.0811 m/ns)	5890	42	-38.26	+38.08	0.30	8.52	-16.4 to +17.0
(d)	Single mean velocity (0.0821 m/ns)	5890	36	-38.37	+40.54	1.54	8.71	-15.5 to +18.6
(e)	Single modal velocity (0.0827 m/ns)	5890	45	-36.20	+38.73	2.30	8.64	-14.6 to +19.2
	Single modal velocity (0.0796 m/ns)	5890	46	-37.84	+33.61	-1.47	8.31	-17.8 to +14.8

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Table 4 - Summary of Success Rates for Recording Reflection Signals Using Copper Wires Embedded in Grout Pipes

Wire Type	No. of Sites	No. of Nails Tested	No. of test with no signal from one wire embedded in grout tube	No. of test with no signal from both wires embedded in grout tube	No. of test with no signal from normal sensor wire	No. of test with signal from both wires embedded in grout tube
Type A (1 mm dia.)	2	229	9 (3.9%)	1 (0.4%)	0 (0.0%)	219 (95.6%)
Type B (0.5 mm dia.)	3	175	6 (3.4%)	0 (0.0%)	2 (1.1%)	169 (96.6%)

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Table 5 - Variation of Pulse Propagation Velocity Measured Using Grout Pipe Embedded Wires in Comparison with Normal External Wires

Wire Type	Testing Configuration	No. of Tests	Min Velocity (m/ns)	Max Velocity (m/ns)	Mean Velocity, μ (m/ns)	Standard Deviation, σ (m/ns)	Coefficient of Variation, (σ/μ) COV (%)	Error in Length Estimation by Single Mean Velocity		Error in Length Estimation by Median Velocity at Individual Site	
								μ (%)	σ (%)	μ (%)	σ (%)
Type A Copper Wires Embedded in Grout Pipe (1 mm dia.)	Wire A1 and Bar	223	0.1085	0.1543	0.1228	0.0052	4.21				
	Wire A2 and Bar	224	0.1084	0.1566	0.1224	0.0060	4.87				
	Avg. of above	219	0.1131	0.1554	0.1225	0.0043	3.54	-0.12	3.34	0.40	3.32
Normal Sensor Wire	Green Wire and Bar	226	0.0697	0.0973	0.0815	0.0057	7.01				
Type B Copper Wires Embedded in Grout Pipe (0.5 mm dia.)	Wire B1 and Bar	172	0.0767	0.1402	0.1008	0.0103	10.18				
	Wire B2 and Bar	171	0.0794	0.1756	0.1030	0.0116	11.29				
	Avg. of above	169	0.0871	0.1323	0.1012	0.0064	6.32	0.37	5.94	0.45	5.94
Normal Sensor Wire	Green Wire and Bar	82	0.0636	0.0858	0.0738	0.0049	6.65				
	Black Wire and Bar	90	0.0712	0.1039	0.0846	0.0063	7.43				

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Table 6 - Sampling Strategy - Minimum Sample Size

Lot Size	Minimum Sample Size
≤ 25	5
26 to 50	8
51 to 90	13
91 to 150	20
151 to 280	32
281 to 500	50
501 to 1200	80

Table 7 - Sampling Plans Achieving Consumer's Risk Quality of ≤ 20% for Different Lot Sizes

Lot Size	Single Sampling Plan		
	Sample size, n_0	Consumer's risk quality (% non-conforming)	Alert Criterion
			No. of nonconforming nails with anomalous TDR results
	For consumer's risk quality of ≤ 20%		
≤ 50	10	≈ 20	0
51 to 90	13	16.2	0
91 to 150	20	18.1	1
151 to 280	32	19.7	3
281 to 500	50	17.8	5
501 to 1200	80	18.6	10

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Table 8 - Proposed Sampling Plans for TDR Testing

Lot Size		Minimum number of soil nails to be tested by TDR	Alert Criterion: No. of nonconforming nails with anomalous TDR results
≤ 50	≤ 25	$10 \rightarrow 5$ (Note 3)	0
	26 to 50	$10 \rightarrow 8$ (Note 3)	0
51 to 90		13	0
91 to 150		20	1
151 to 280		32	3
281 to 500		50	5
501 to 1200		80	10

Notes:

(1) Soil nails shall be divided into sample lots with same type of wire. Division of the sample lot should consider factors such as progress of the soil nail installation, availability of access for conducting tests and subsequent works, if found necessary, etc.. The size of sample lots shall generally be greater than 50 nails where possible.

(2) Anomalous TDR result means that the deduced length is less than 85% of the specified length.

(3) For lot sizes ≤ 50, it is suggested that the minimum sample size may be further reduced to 8 for lot size > 25 and 5 for lot size ≤ 25 if the alternative option of using a minimum of 3 calibration nails (with enhanced site supervision) on each site to derive the reference propagation velocity is adopted in lieu of the use of median velocity at each site.

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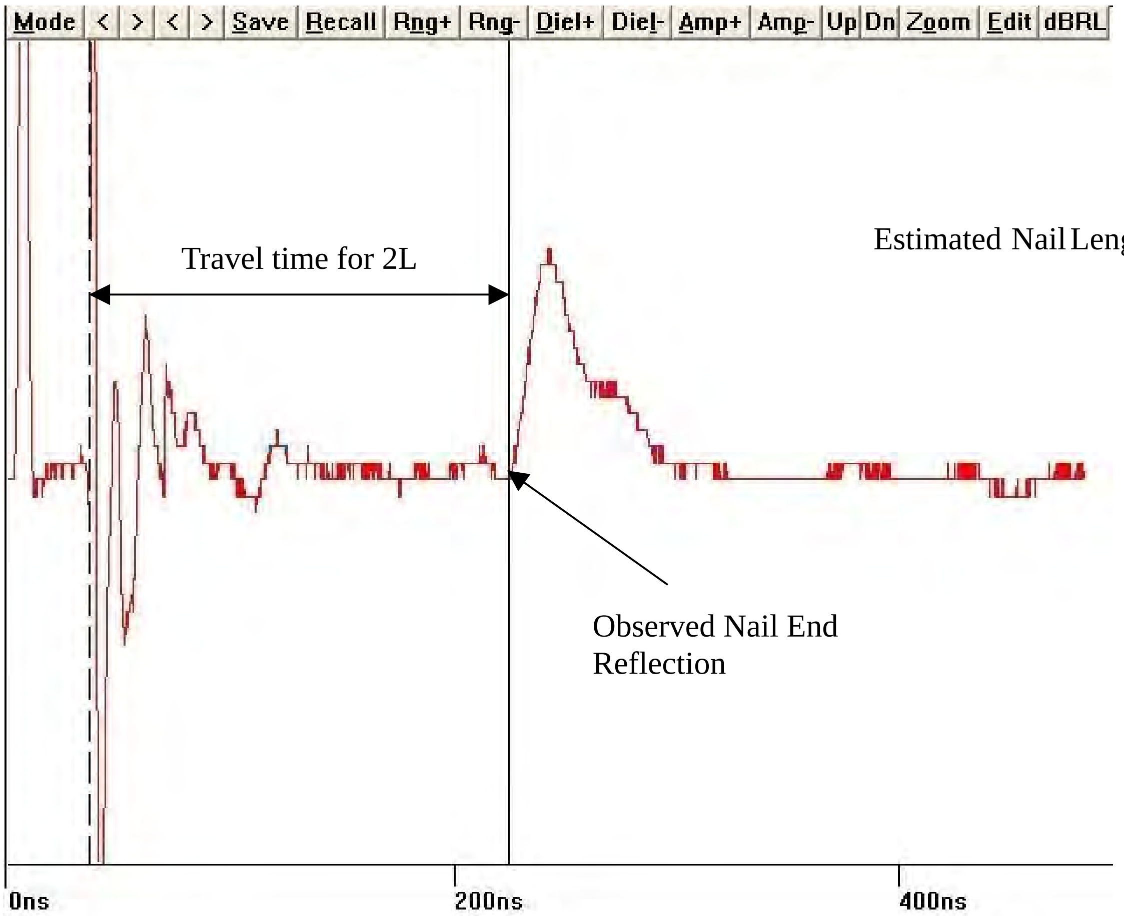

Typical TDR response from a steel soil nail with pre-installed electric wire

$$\text{Estimated Nail Length} = \frac{\text{Propagation velocity} \times \text{travel time}}{2}$$

Propagation velocity Vp, is given by:

$$Vp = 1 / (L*C)^{1/2}$$

where L = cable inductance
C = capacitance

Propagation velocity is a function of both the wire and grout characteristics

Theoretically the velocity in air is 3x times faster than in grout and the velocity in water is 3x slower than in grout

Figure 1 - Time Domain Reflectometry (TDR) - Typical Response and Data Analysis

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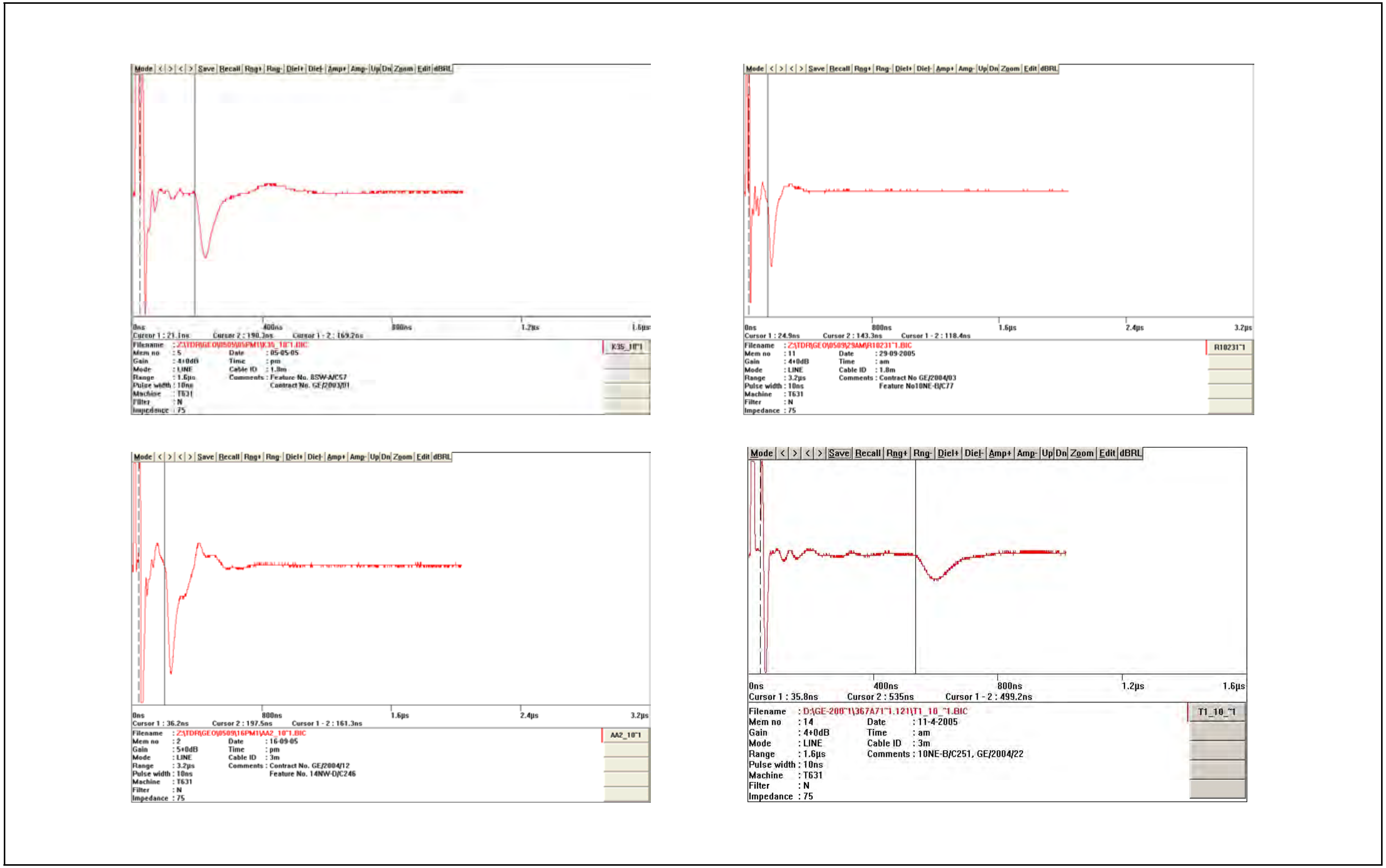

Figure 2 - Inverted TDR Waveforms

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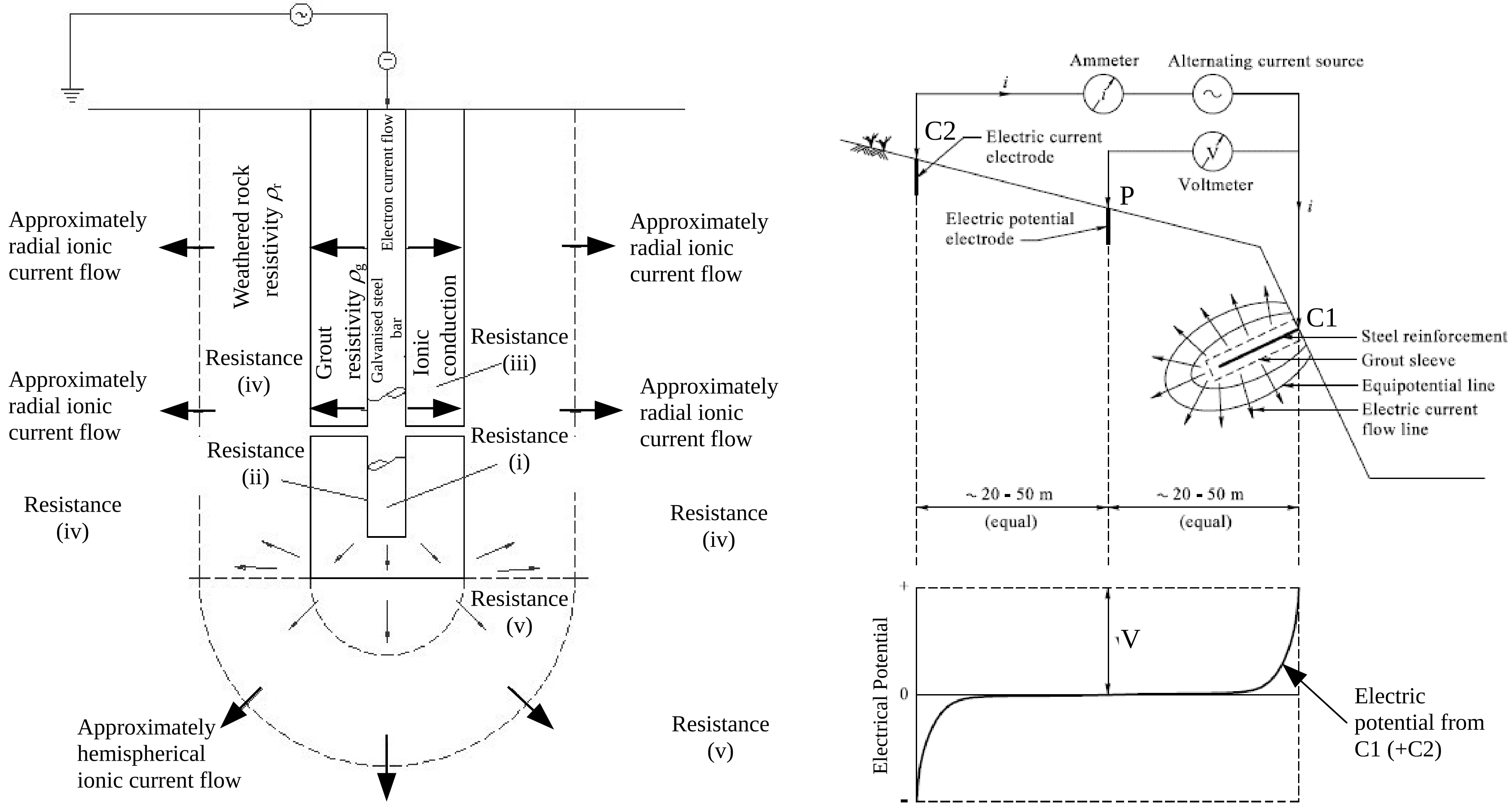

(a) Soil Nail Earth Resistance Re is the Resistance Sum of (i) the Bar, (ii) the Contact, (iii) the Grout Annulus, and (iv) the Ground Space

(b) Typical Setup of Electrical Resistance Method (Extracted from GEO Report No.176)

Figure 3 - Electrical Resistance Method - Method of Measurement and Fundamental Theory

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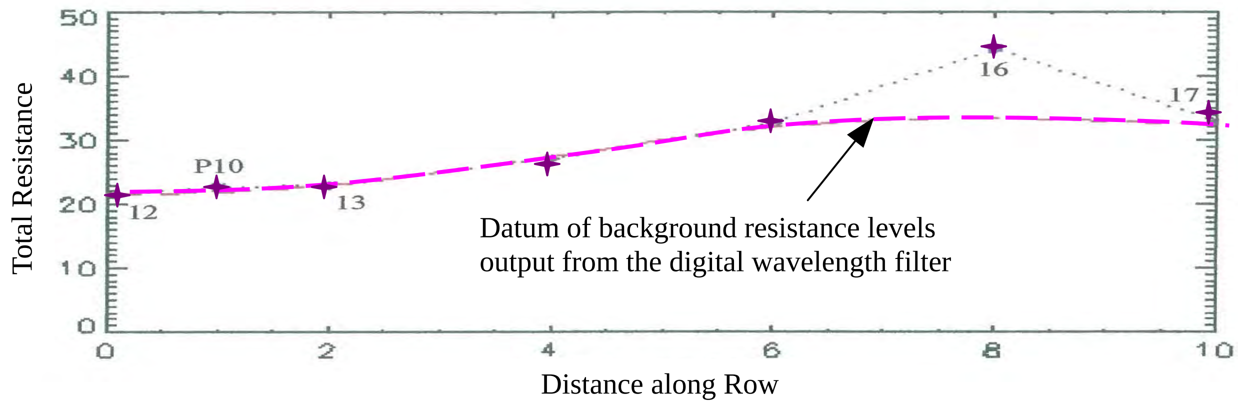
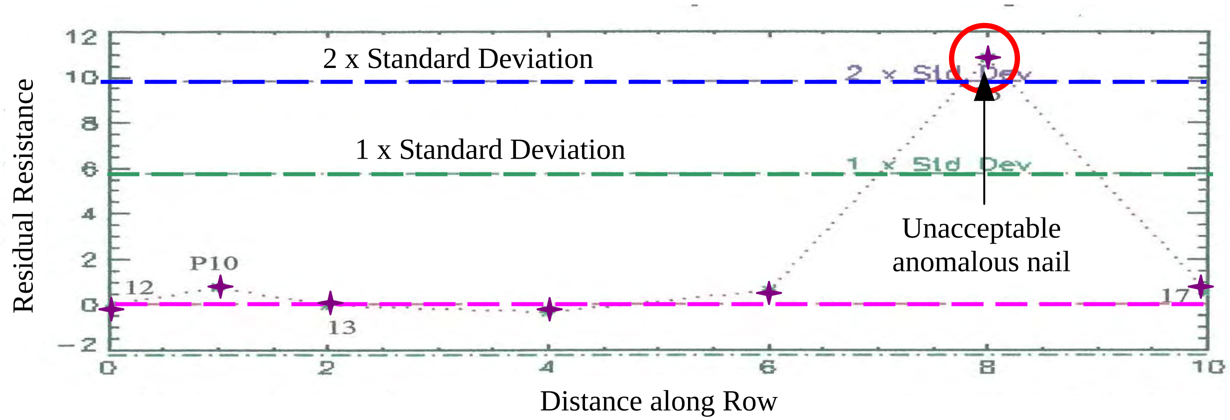


(a) Profile Resistance Data Filtered with a Controlled Wavelength Filter



(b) Discrimination of “Abnormality” by Application of a Simple Comparative Statistical Measure

Figure 4 - Electrical Resistance Method - Data Analysis

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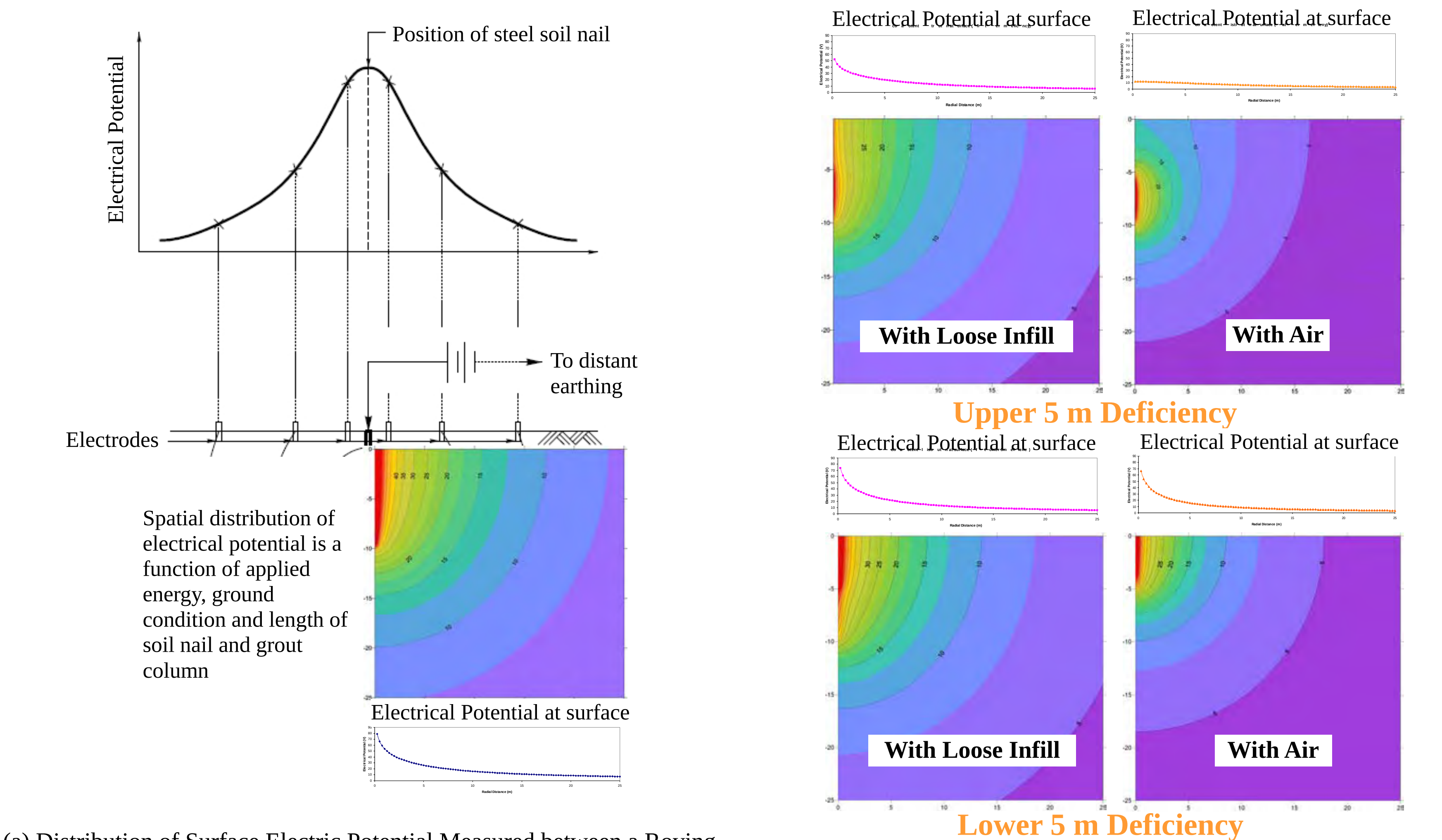

(a) Distribution of Surface Electric Potential Measured between a Roving Potential Electrode and Soil Nail Bar Head in a Radial Pattern

(b) Theoretical Tests Demonstrating Different Electric Potential Gradients for Upper and Lower Grout Deficiencies

Figure 5 - 'Mise a la Masse' Method

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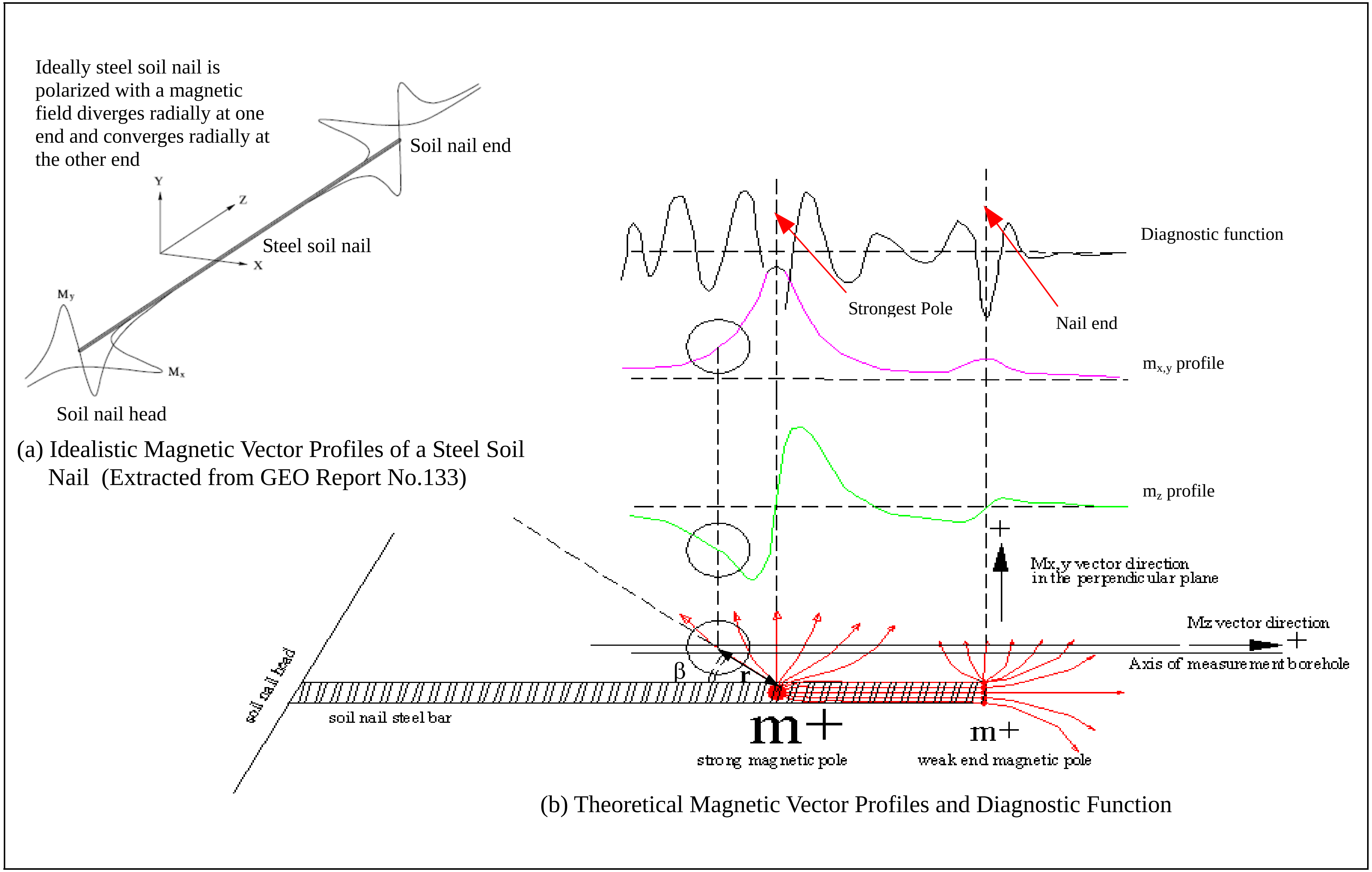

(a) Idealistic Magnetic Vector Profiles of a Steel Soil Nail (Extracted from GEO Report No.133)

(b) Theoretical Magnetic Vector Profiles and Diagnostic Function

Figure 6 - Vector Magnetic Method (Magnetometry)

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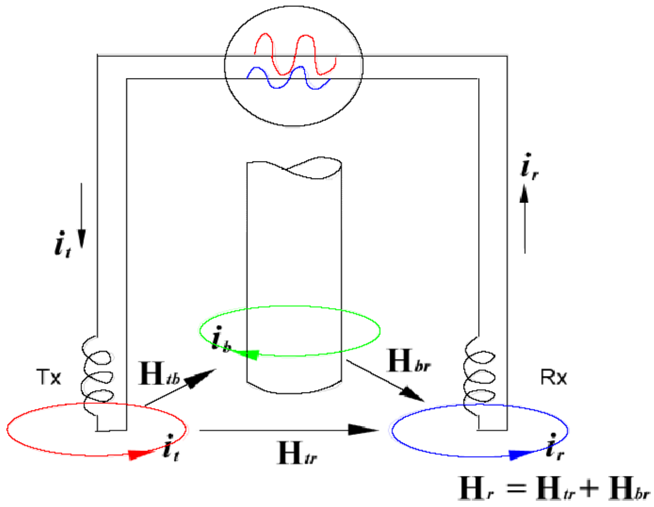
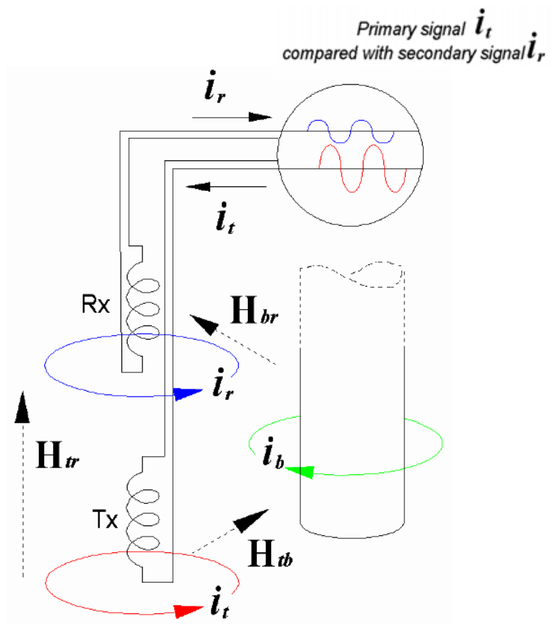


(a) Original Twin Tube System of the Electromagnetic Induction Method



(b) Possible Modification to Present System

Legend:

i_t Primary current in transmitter coil Tx
i_b Secondary eddy current induced in the bar by H_{tb}
i_r Resultant current induced in receiver coil Rx by H_r
H_{tr} Magnetic flux coupling directly between Tx and Rx
H_{tb} Magnetic flux coupling between Tx and the bar
H_{br} Secondary magnetic flux coupling between the bar and Rx
H_r Resultant magnetic flux in Rx

Figure 7 - Electromagnetic Induction Method

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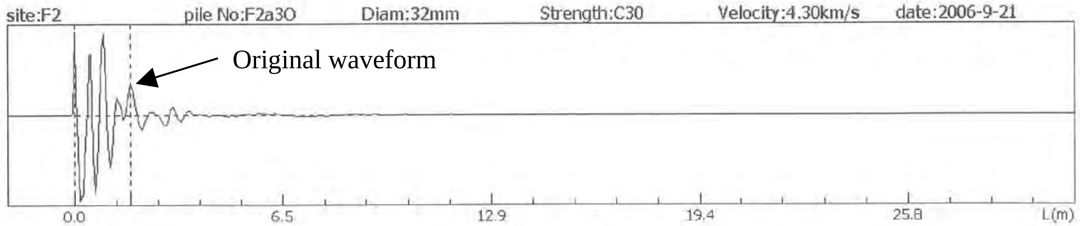
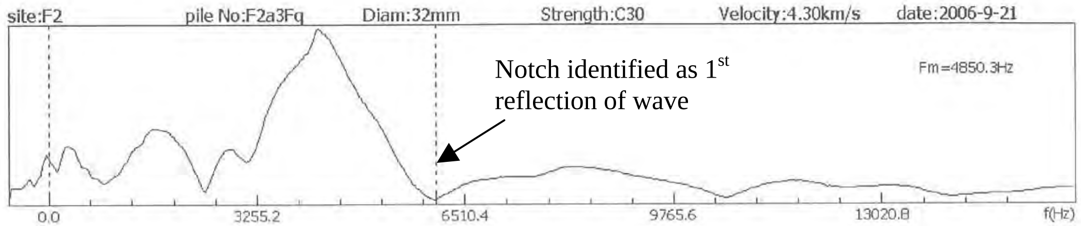
(a) Chak's Socket

(b) Impulse Manually Imparted by a Pin

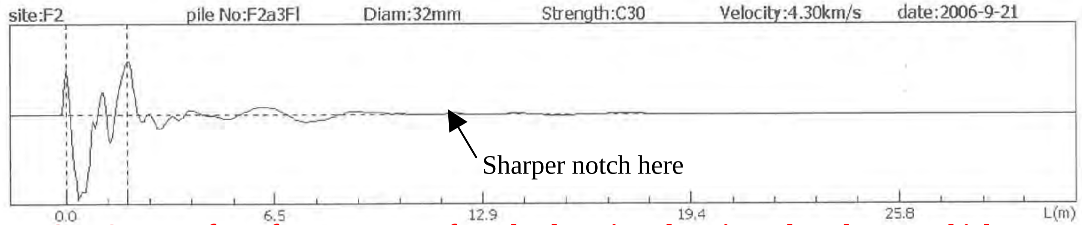
(c) Hammers and Pins for Striking



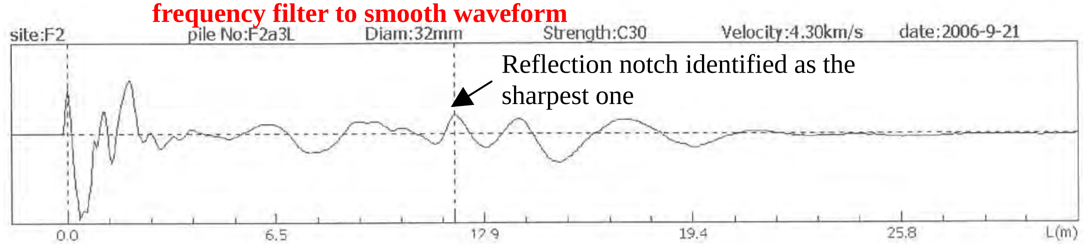
Step 0 - original waveform



Step 1 - Transform time domain waveform to frequency domain



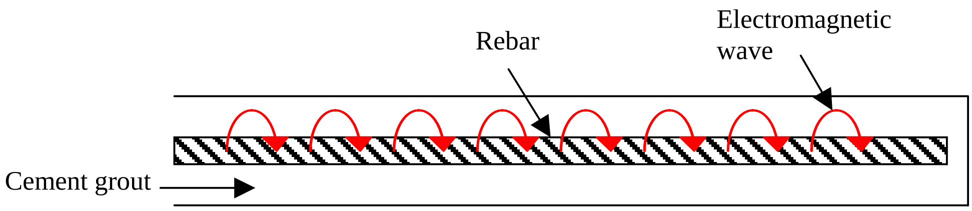
Step 2 - Transform frequency waveform back to time domain and apply a very high frequency filter to smooth waveform



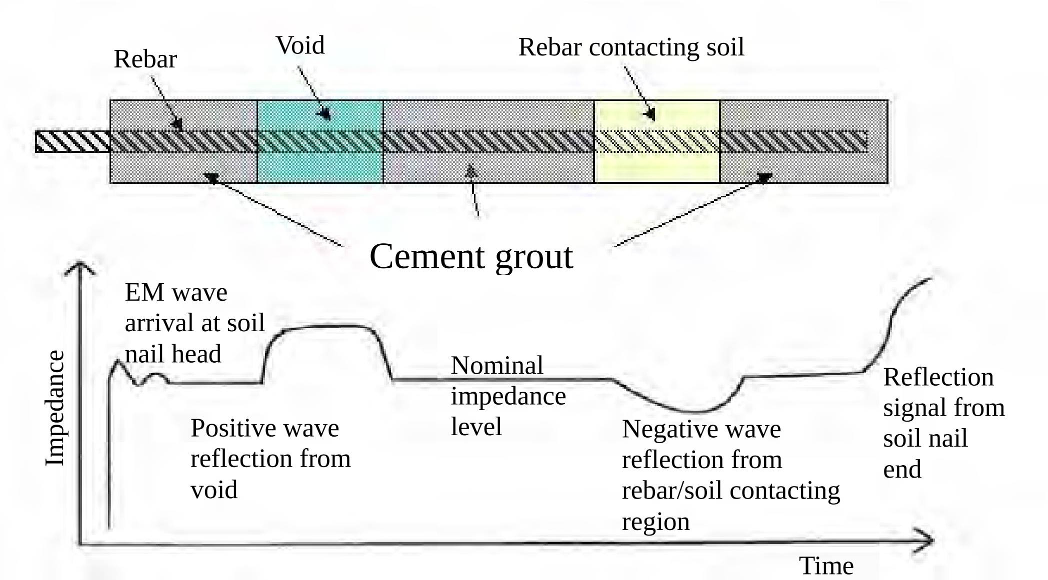
Step 3 - Magnify waveform using exponential factor (e.g. 14.4x)

(d) Example Test Result and Interpretation of Sonic Impulse Method

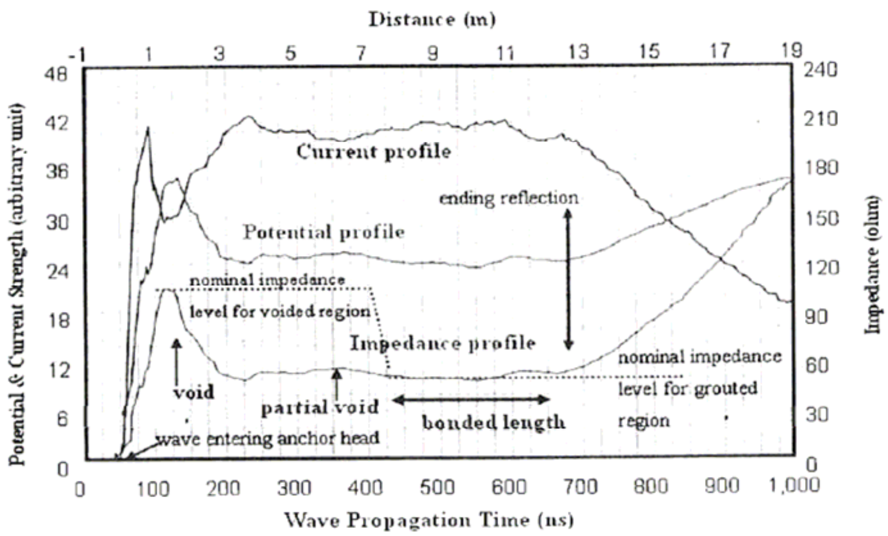
Figure 8 - Sonic Impulse Method (Sonic Echo Method)



(a) Surface Electromagnetic Waves Propagating along a Conductor (Tang, 2004)



(b) Soil Nail with Anomalies along Rebar (above) and Corresponding Idealistic Impedance Profile (below) (Tang, 2004)



(c) Example of Surface Wave TDR Result Diagram Comprising Potential, Current and Impedance Profiles (Tang, 2004).

Figure 9 - Surface Wave Time Domain Reflectometry

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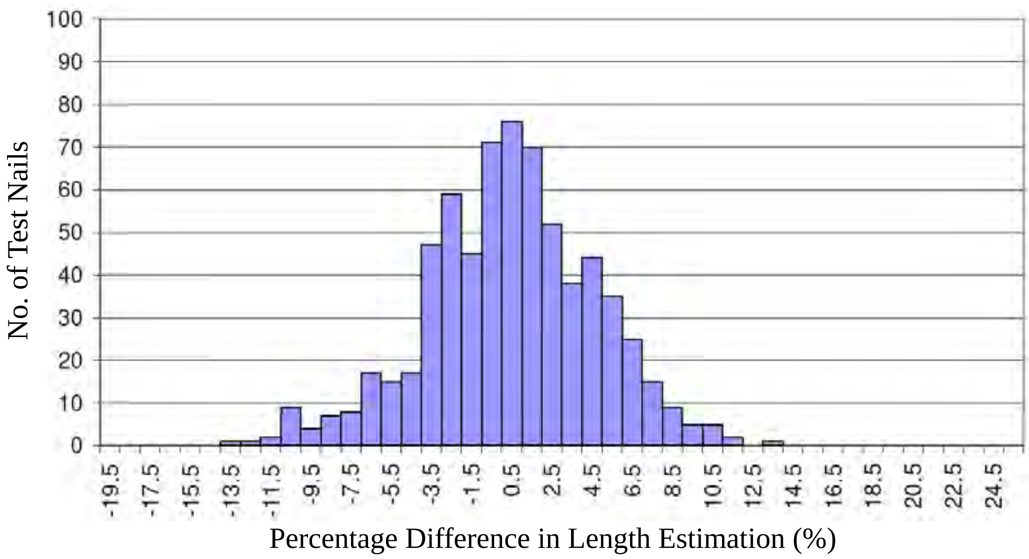
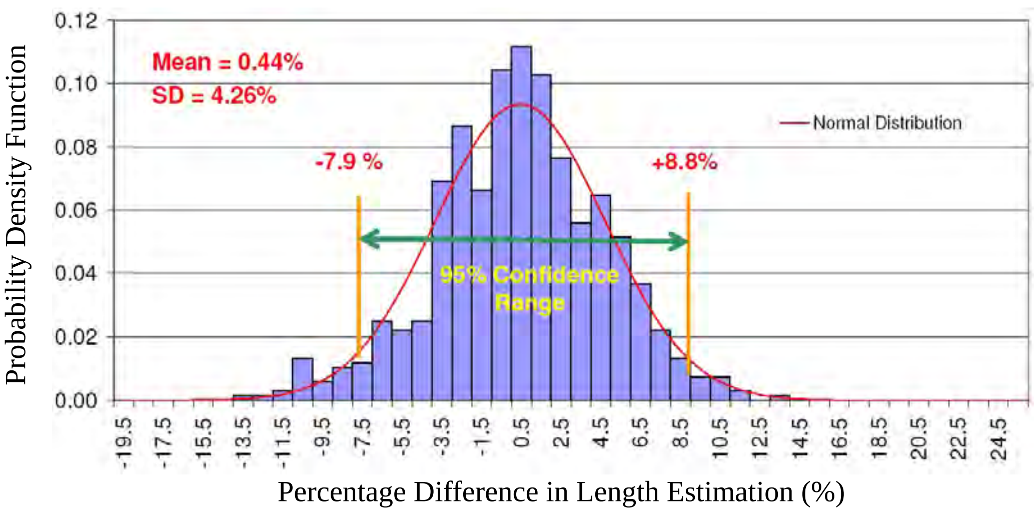


(a) Frequency Distribution of Length Estimation Error by Calibration



(b) Probability Density Function of Length Estimation Error by Calibration

Figure 10 - Statistical Analysis of Initial 700 Controlled TDR Tests

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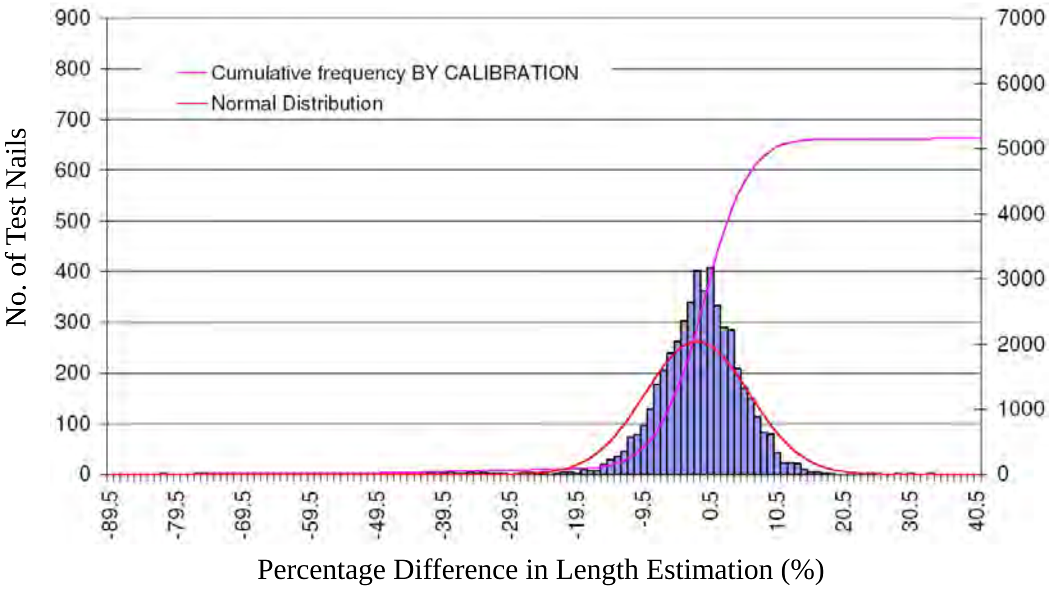
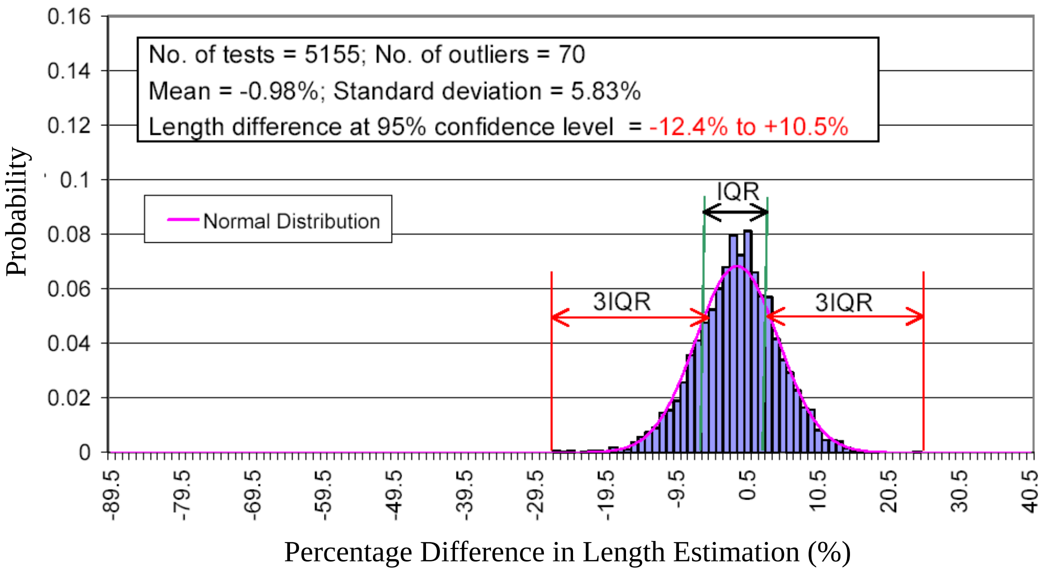


(a) Frequency Distribution of Percentage Length Difference by Calibration



(b) Probability Density Function of Percentage Length Difference by Calibration

Figure 11 - Statistical Analysis of Routine TDR Tests - Case (a) Length Estimation by Use of Calibration Nails

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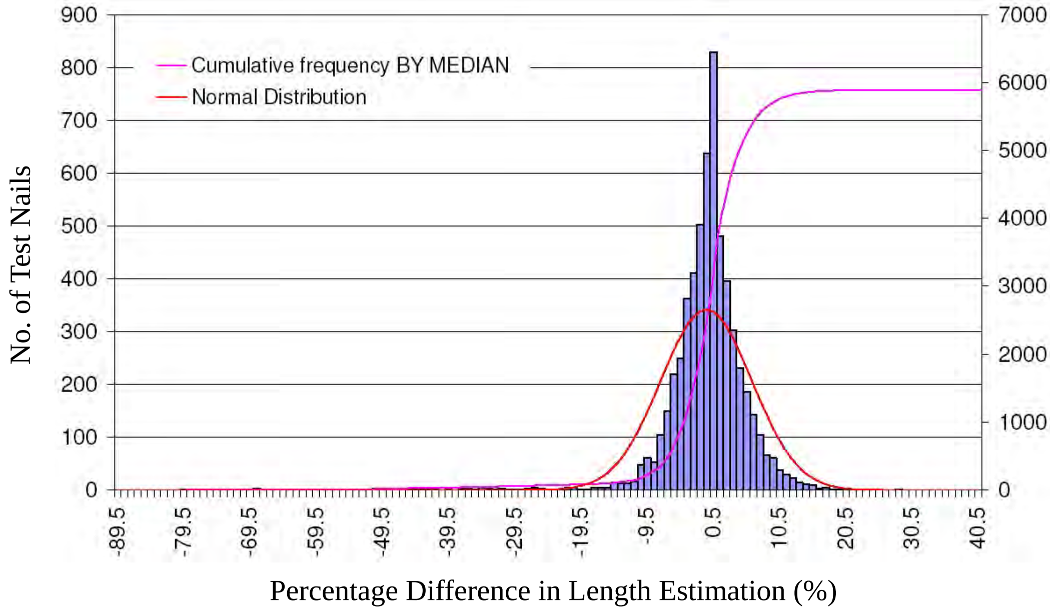
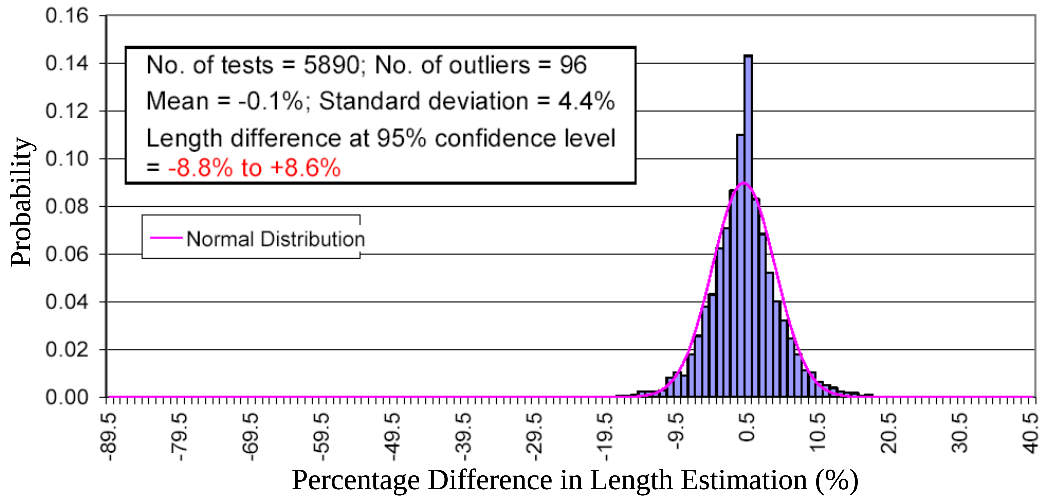


(a) Frequency Distribution of Percentage Length Difference by Median Velocity at Each Site



(b) Probability Density Function of Percentage Length Difference by Median Velocity at Each Site

Figure 12 - Statistical Analysis of Routine TDR Tests - Case (b) Length Estimation by Use of Median Velocity at Each Site

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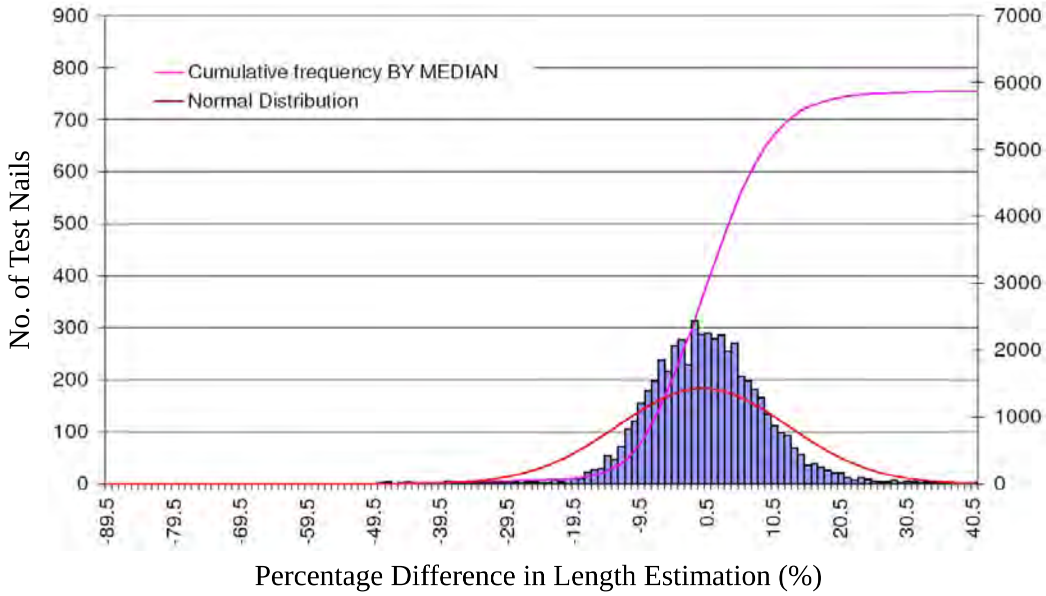
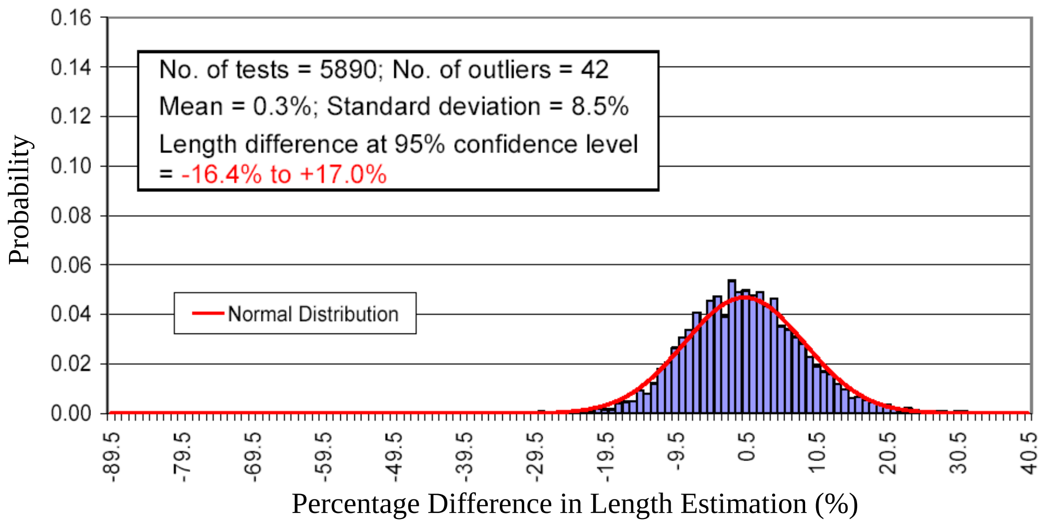


(a) Frequency Distribution of Percentage Length Difference by Single Median Velocity of All Sites



(b) Probability Density Function of Percentage Length Difference by Single Median Velocity of All Sites

Figure 13 - Statistical Analysis of Routine TDR Tests - Case (c) Length Estimation by Use of Single Median Velocity of All Sites

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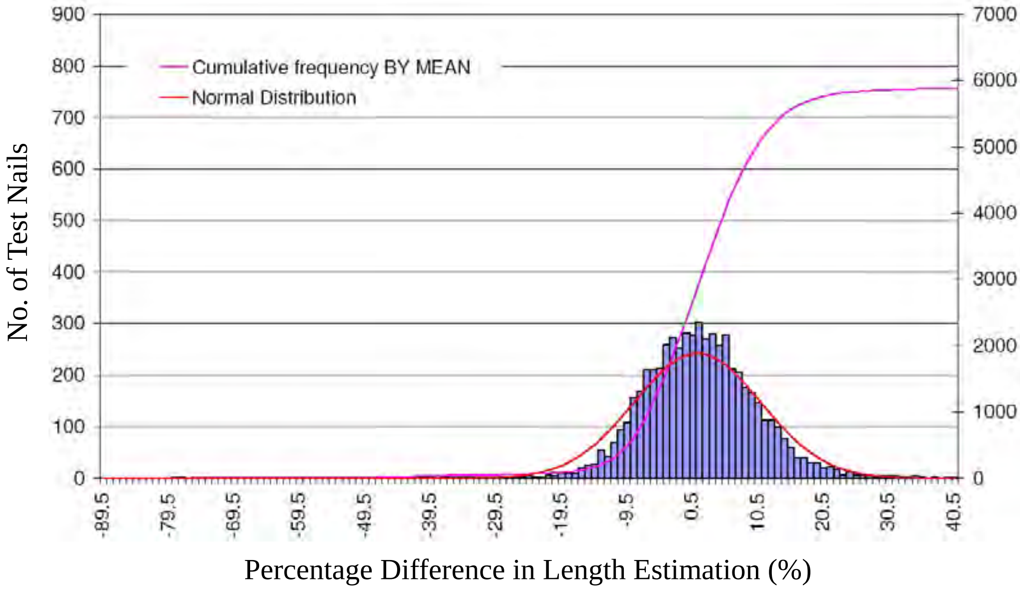
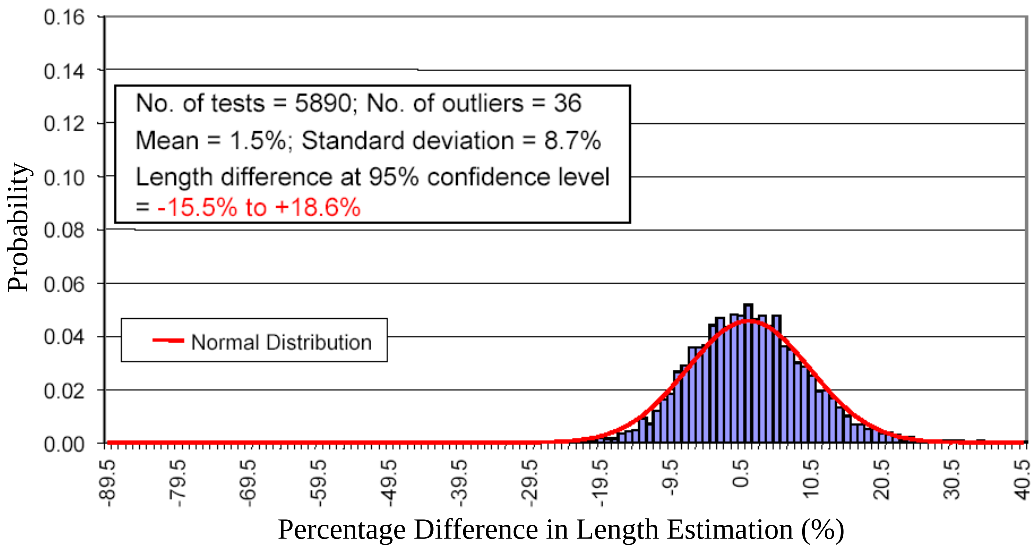


(a) Frequency Distribution of Percentage Length Difference by Single Mean Velocity of All Sites



(b) Probability Density Function of Percentage Length Difference by Single Mean Velocity of All Sites

Figure 14 - Statistical Analysis of Routine TDR Tests - Case (d) Length Estimation by Use of Single Mean Velocity of All Sites

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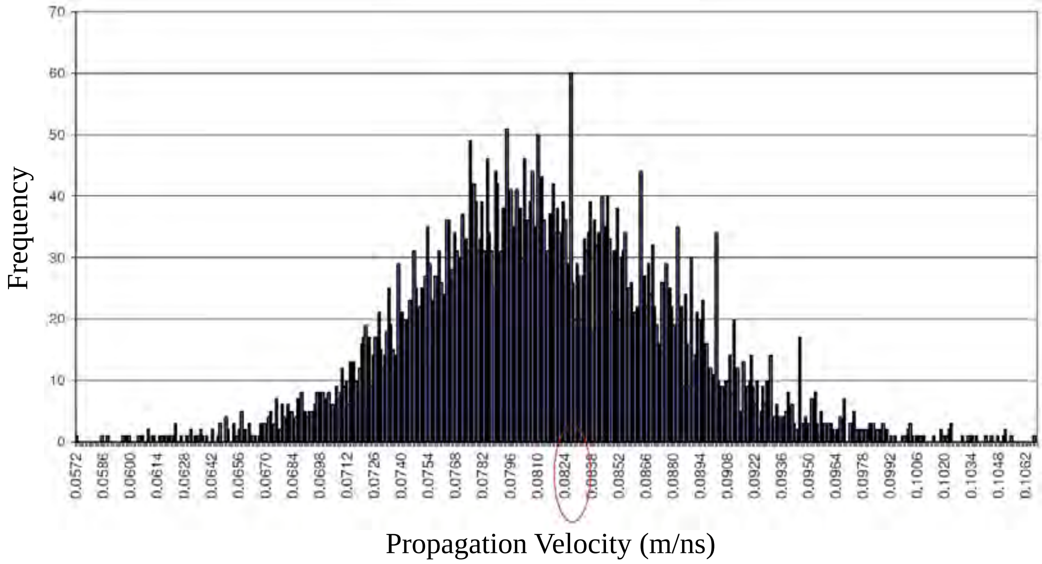
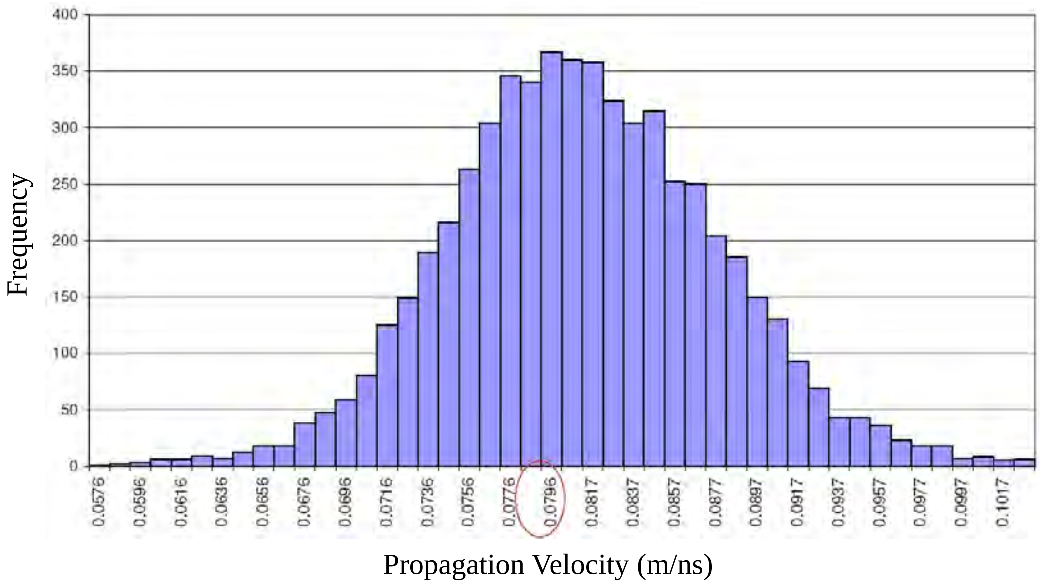


(a) Frequency of Modal Velocity of All Sites (Range divided into interval of 0.0001 m/ns)



(b) Frequency of Modal Velocity of All Sites (Range divided into interval of 0.001 m/ns)

Figure 15 - Statistical Analysis of Routine TDR Tests - Case (e) Length Estimation by Use of Single Modal Velocity of All Sites

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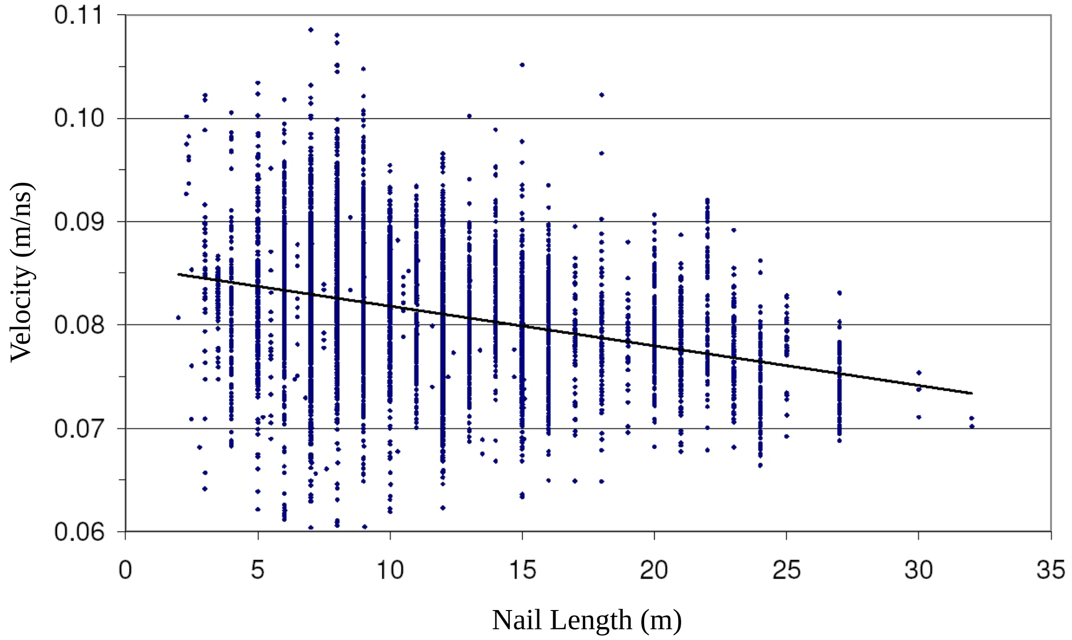
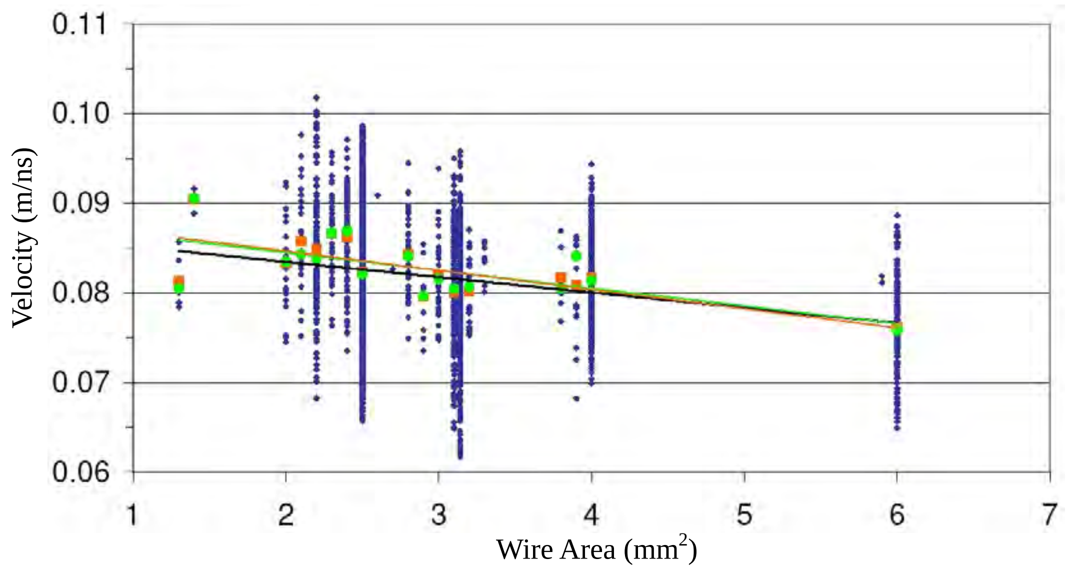


(a) Variation of Pulse Propagation Velocity with Nail Reinforcement Length



(b) Variation of Pulse Propagation Velocity with Cross-sectional Area of Wire

Legend:

Mean

Median

Figure 16 - Variation of Pulse Propagation Velocity with Nail Reinforcement Length and Wire Cross-sectional Area

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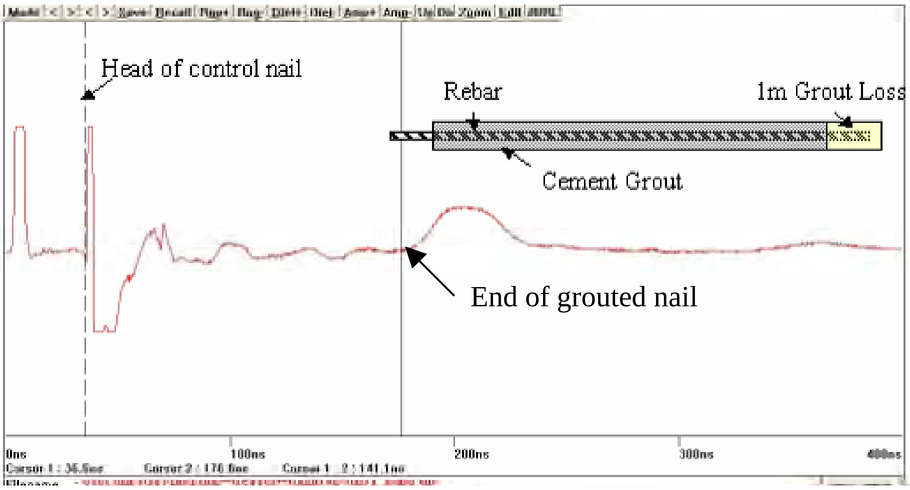

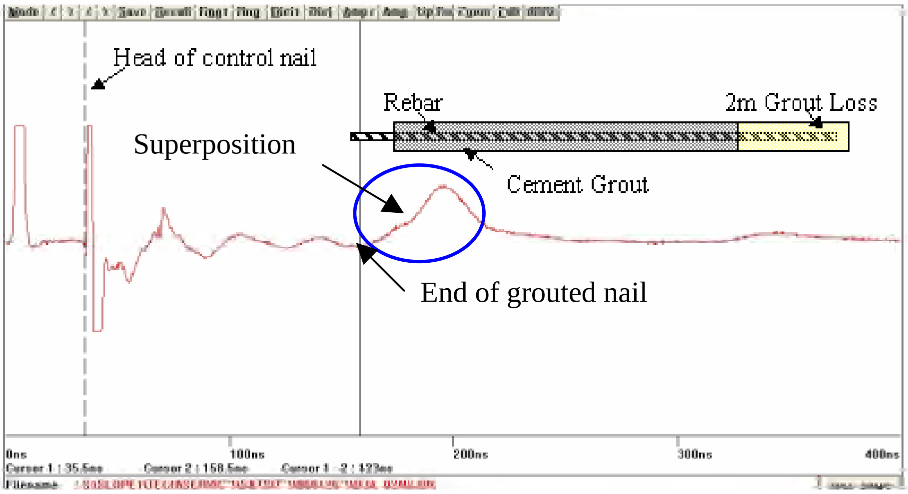

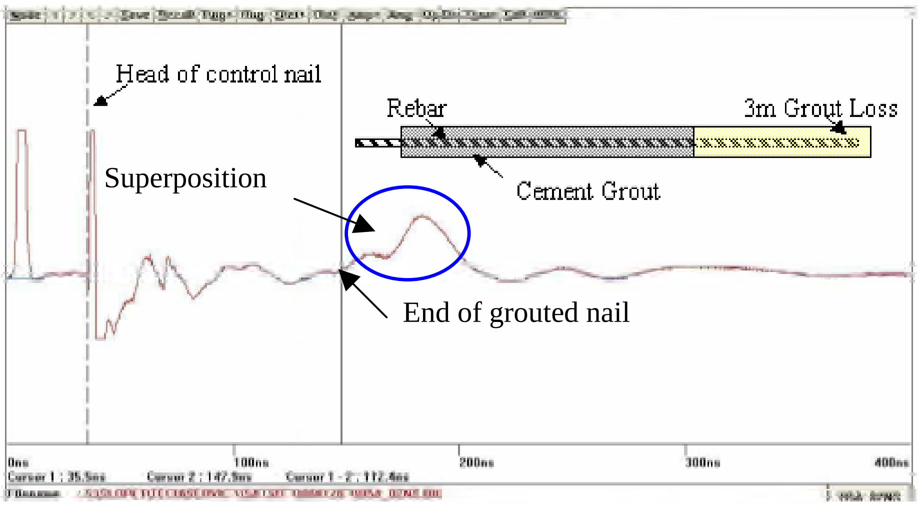

Notes: (1) Grout loss in large size and at nail end could result in superposition waveform.
(2) Small grout loss at nail end cannot be detected.

Figure 17 - Grout Defects Investigation Using TDR (Sheet 1 of 2)

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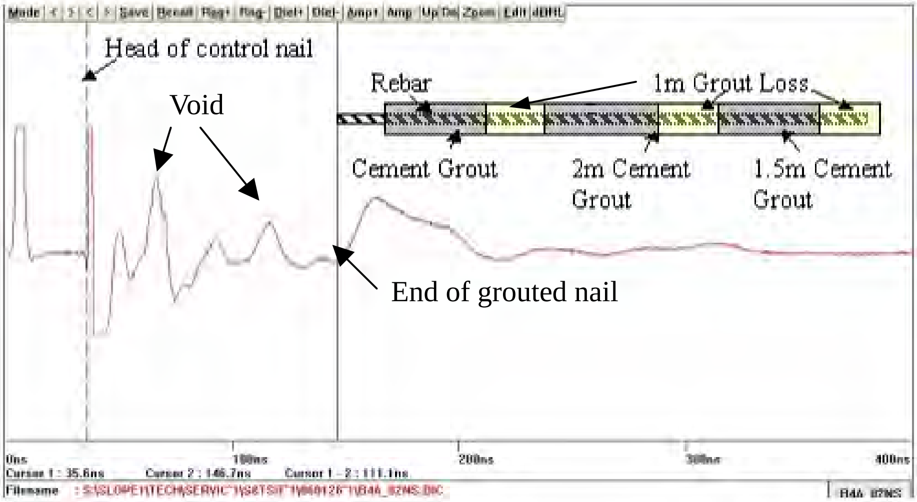

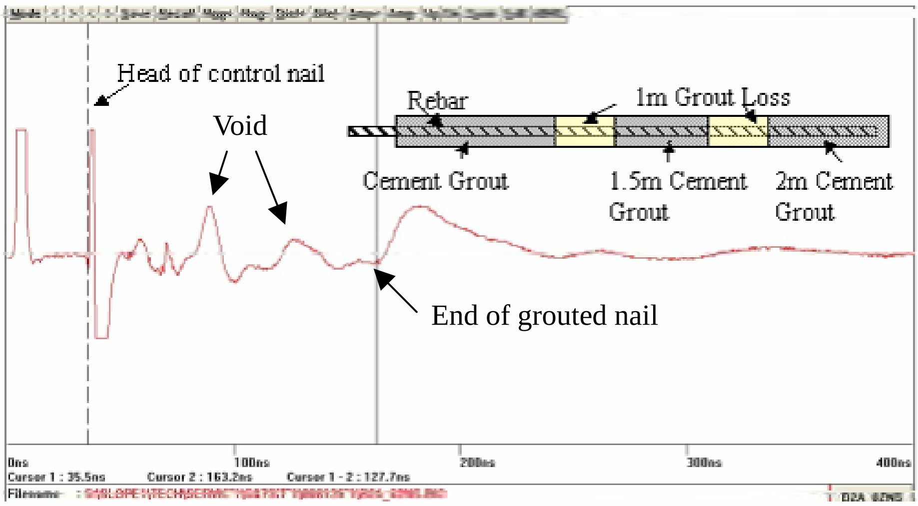

Notes: (1) Approximate location of grout loss could be observed in the waveform.
(2) Amplitude of the waveform does not reflect the actual size of the grout loss.
(3) Grout loss (air) led to apparently shorter soil nails.

Figure 18 - Grout Defects Investigation Using TDR (Sheet 2 of 2)

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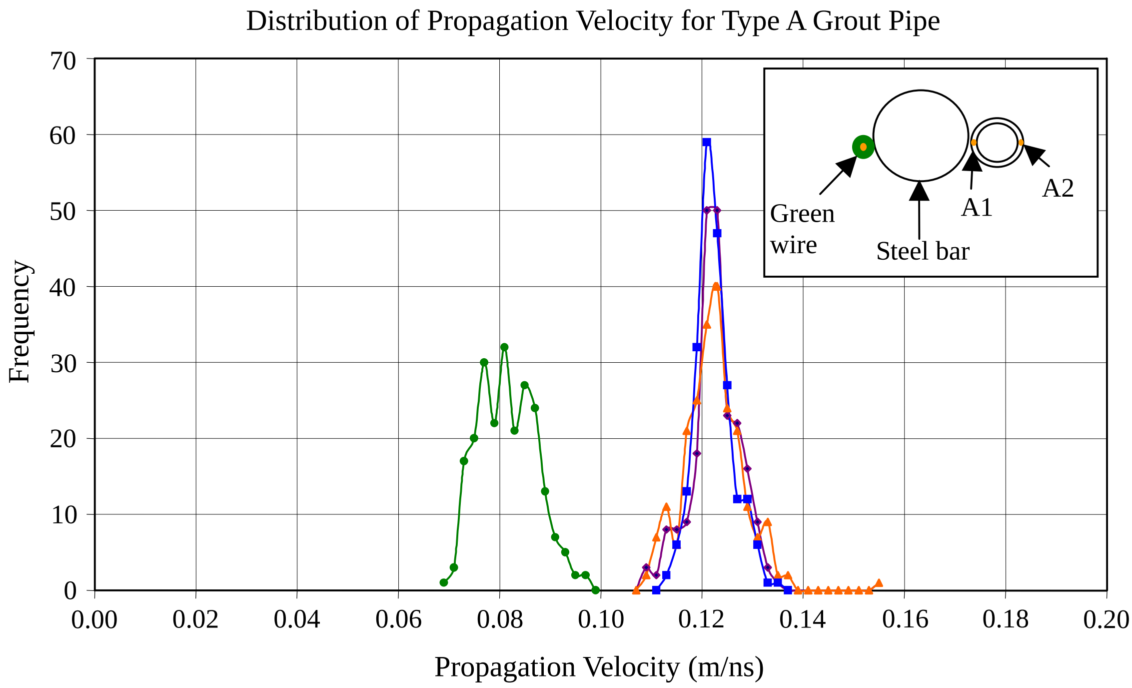
(a) Grout Tube Type A (1 mm dia.)



(b) Distribution of Pulse Propagation Velocity Measured Using Embedded Wires in Grout Pipe Type A in Comparison with Normal External Wire

Legend:

Wire A1 and bar	Wire A2 and bar
Average of A1 and bar, A2 and bar	Green Wire and bar

Figure 19 - Special Investigation of Use of Type A Grout Pipe with Embedded Wires for Improvement of TDR Method

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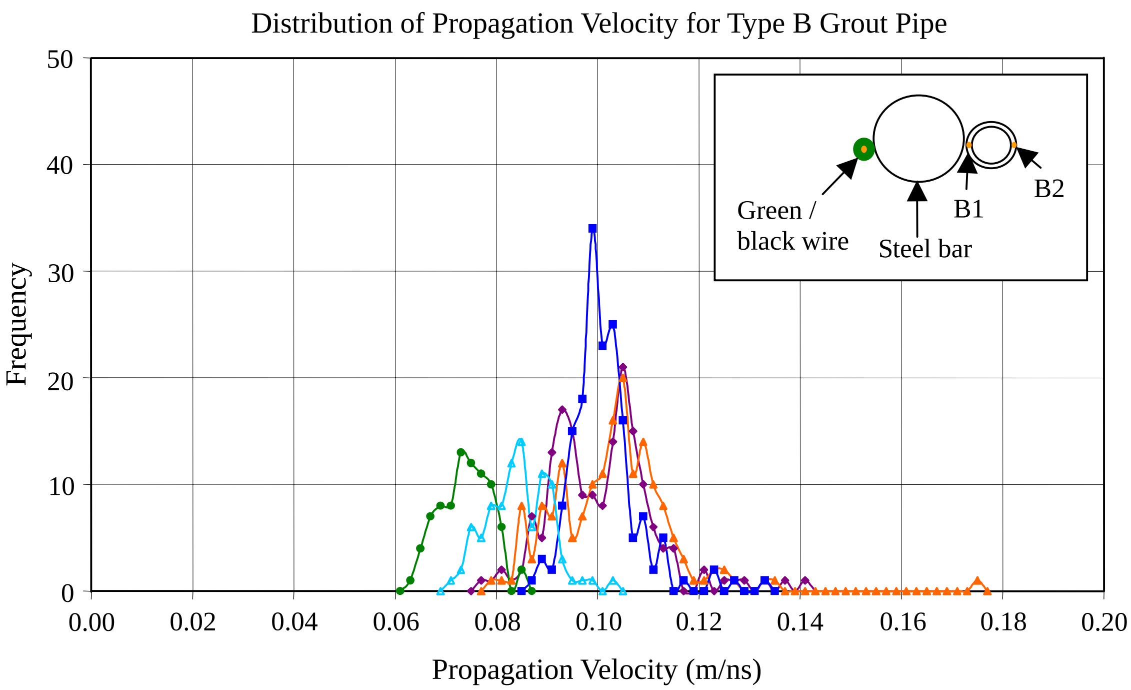
(a) Grout Pipe Type B (0.5 mm dia.)



(b) Distribution of Pulse Propagation Velocity Measured Using Embedded Wires in Grout Pipe Type B in Comparison with Normal External Wire

Legend:

- Wire B1 and bar
- Average of B1 and bar, B2 and bar
- Black Wire and bar
- Wire B2 and bar
- Green Wire and bar

Figure 20 - Special Investigation of Use of Type B Grout Pipe with Embedded Wires for Improvement of TDR Method

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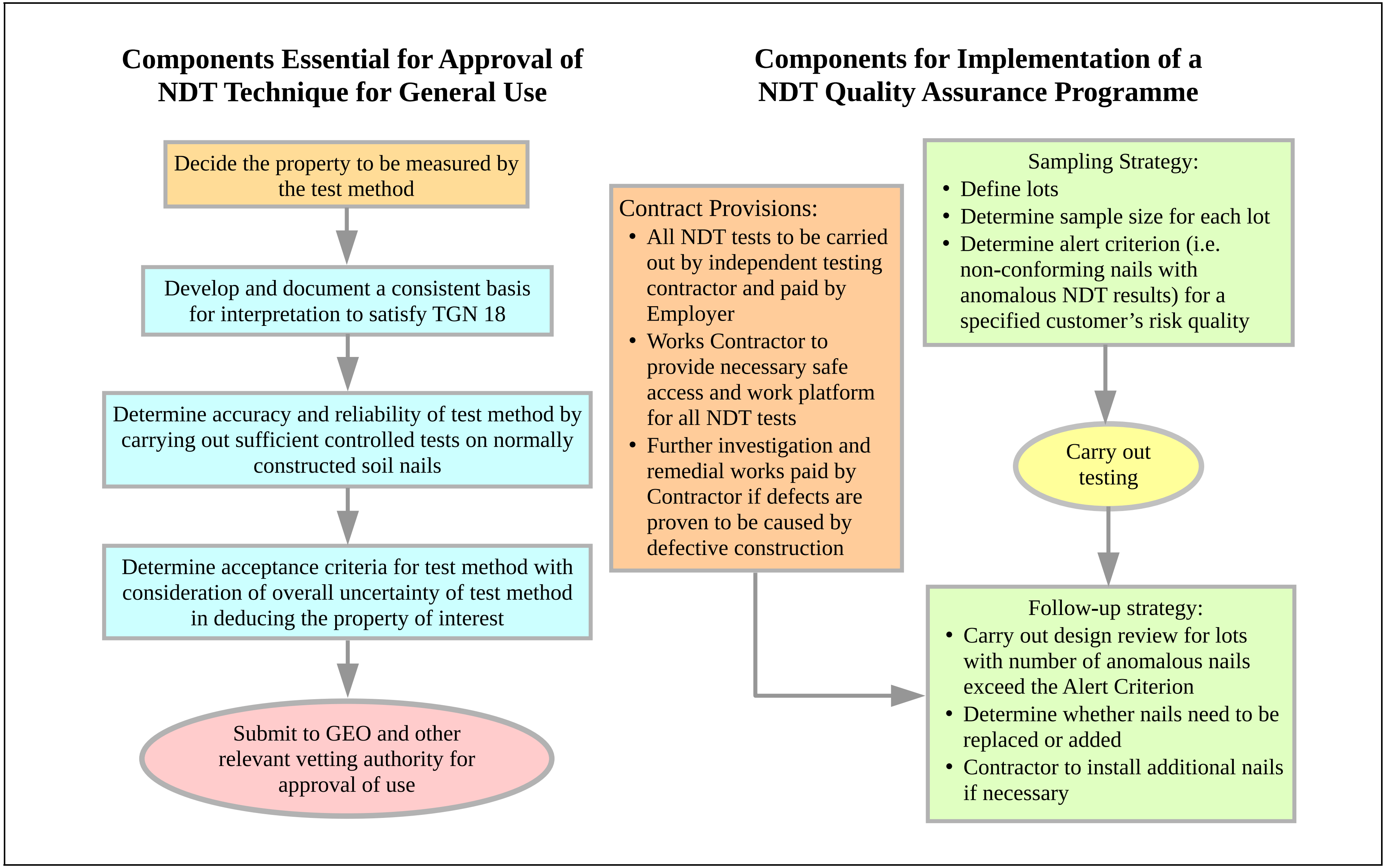

Figure 21a - General Framework for Application of NDT Techniques for Quality Control of Soil Nailing Works

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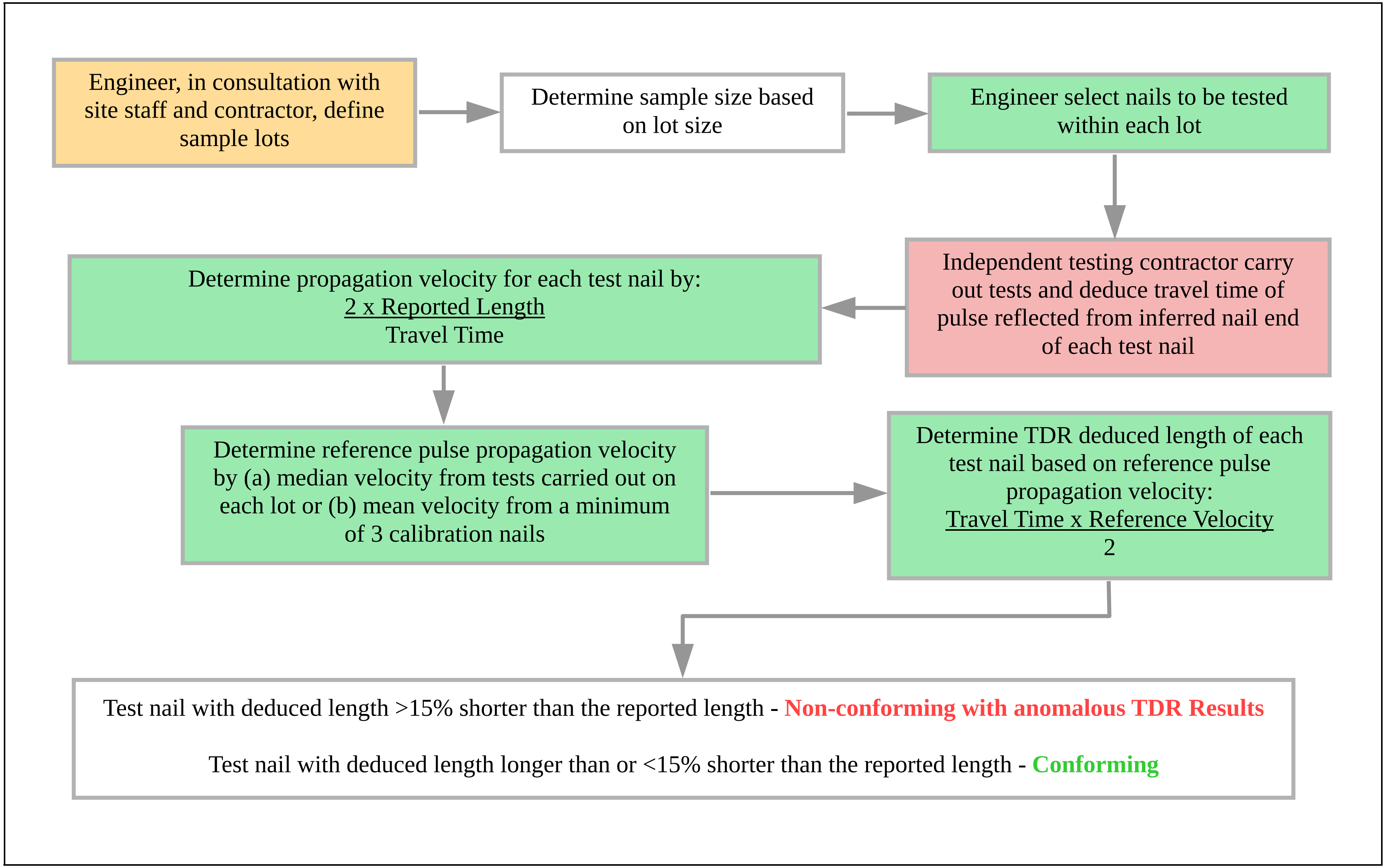

Figure 21b - Application of Proposed Testing Regime to TDR

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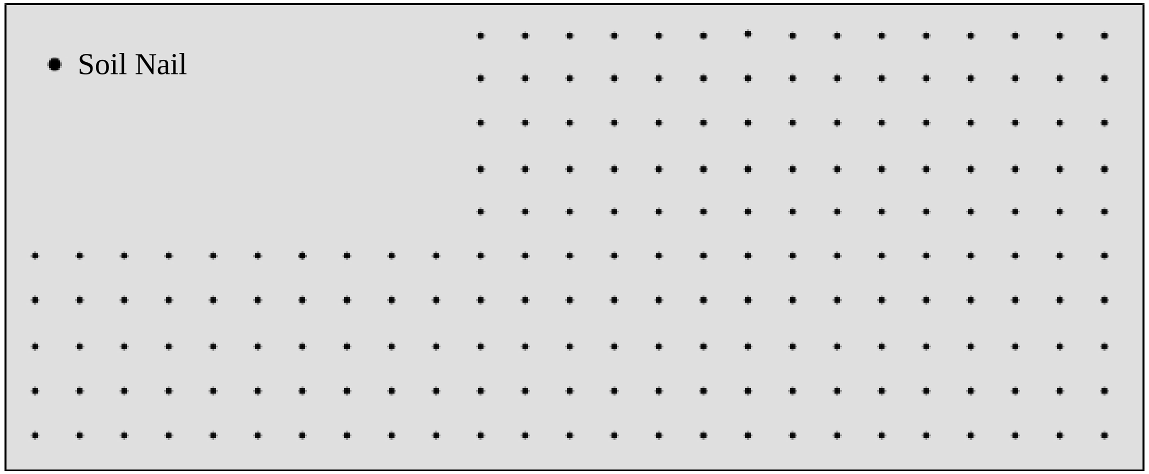
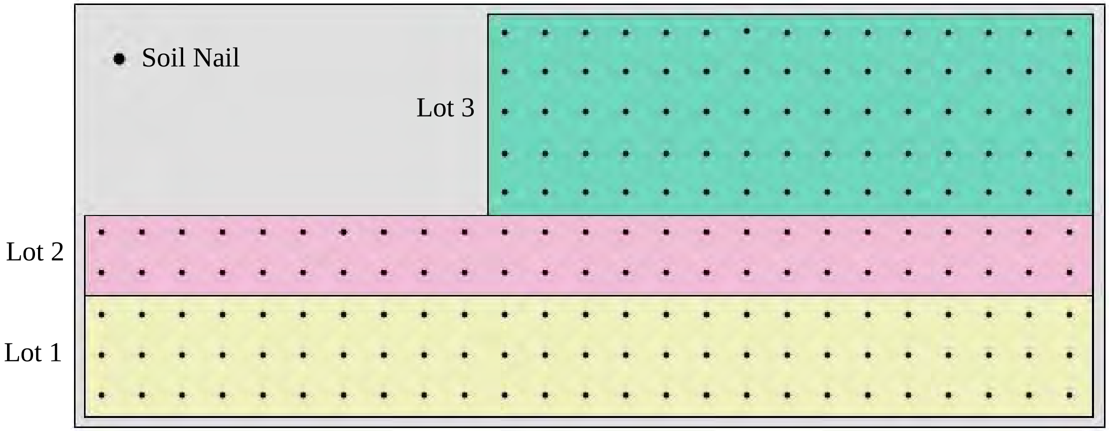


Layout of soil nails (200 nos.)



Lot No.	Nail Length (m)	No. of Nail
Lot 1	9 - 10	75
Lot 2	11 - 12	50
Lot 3	13 - 14	75
	Total:	200

Formation of Lots - Lot Size within range of 51 to 90 $\Rightarrow$ Sample Size = 13

Figure 22 - Application of Proposed Sampling and Testing Framework to TDR Testing (Sheet 1 of 4)

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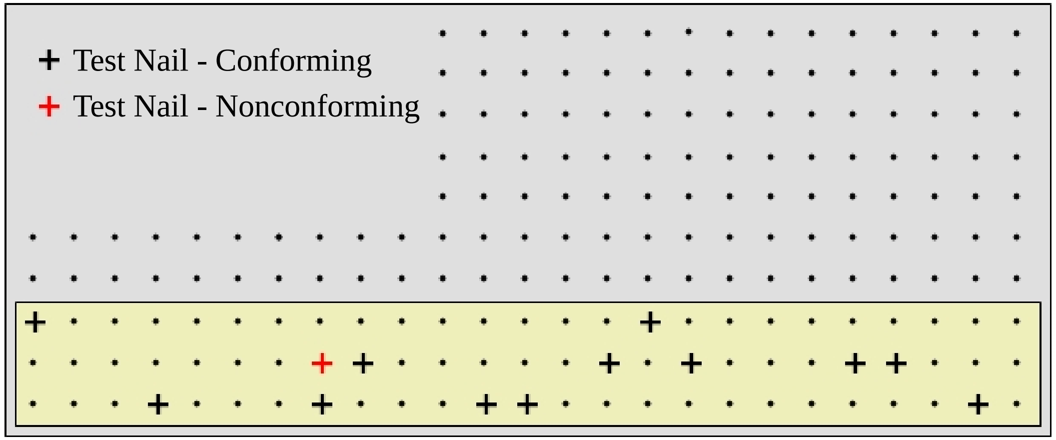
For Lot 1, 13 nails are randomly selected to be tested:

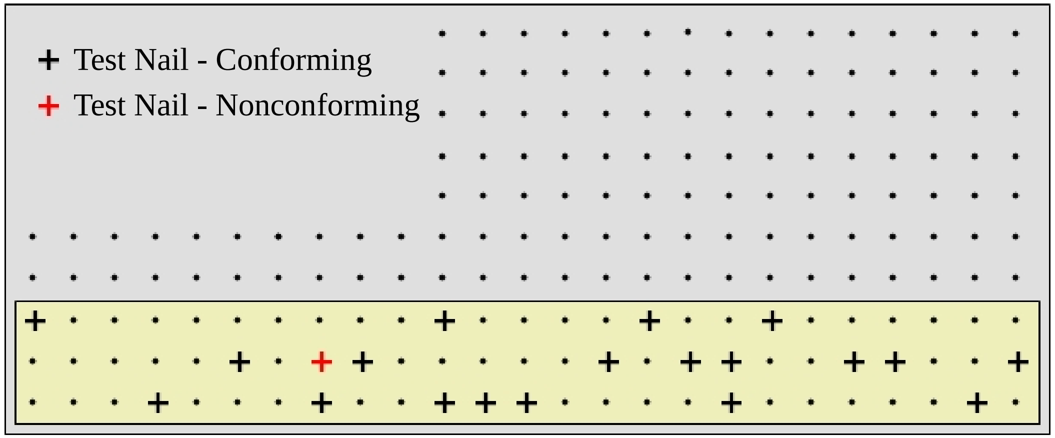
Lot 1



- 1 nonconforming soil nail is detected
- No. of nonconforming soil nails > Number given in the Alert Criterion (0 in first sampling plan)
- 2nd sampling plan, test 7 more nails

For Lot 1 (2nd Sampling Plan), 7 more nails are randomly selected:

Lot 1



- No nonconforming soil nail is detected among these 7 nails,
- Total no. of nonconforming soil nails = number given in the Alert Criterion (i.e. 1 in second sampling plan)
- No more testing is required for Sample Lot 1. Nonconforming soil nail should be replaced or design review should be carried out
- Nails added or replaced shall be subject to TDR tests

Figure 23 - Application of Proposed Sampling and Testing Framework to TDR Testing (Sheet 2 of 4)

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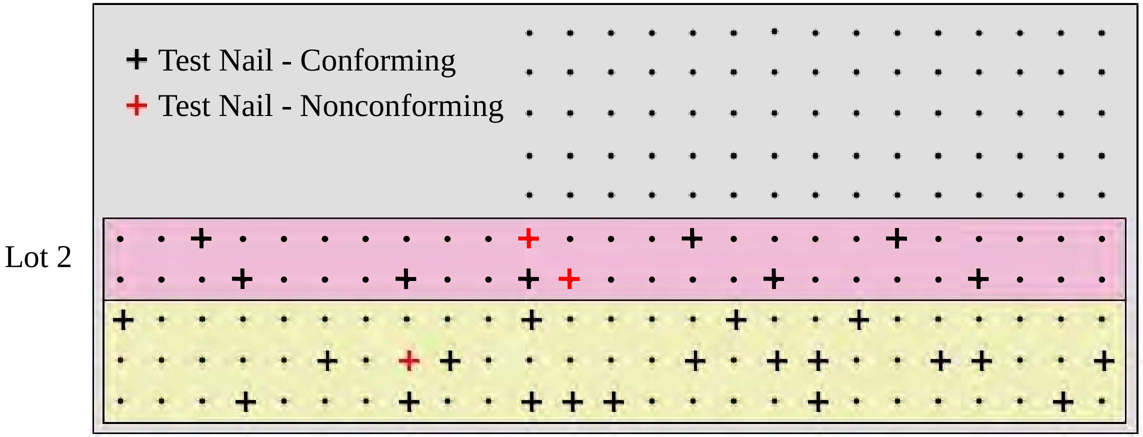
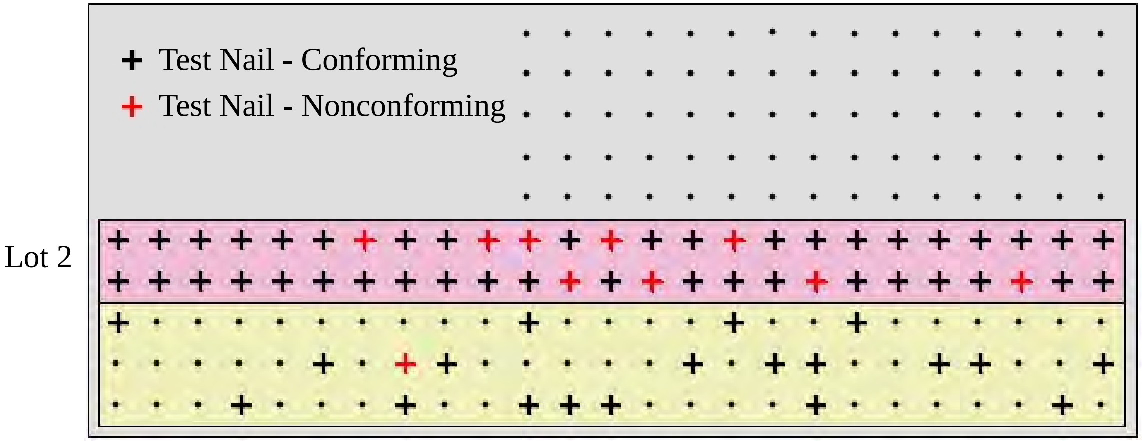
For Lot 2, 10 nails are randomly selected to be tested:



- 2 nonconforming soil nails are detected
- No. of nonconforming soil nails ≥ number given in the Alert Criterion for next sampling plan (i.e. 2)
- Investigation is warranted for Sample Lot 2 to determine the cause and scale of problem

For Lot 2, all remaining nails are then tested and design review carried out:



- Additional nails constructed or further investigation carried out. Decision may be deferred until results of last sample lot is available - depends on many factors
- Nails replaced or added shall be subject to TDR tests

Figure 24 - Application of Proposed Sampling and Testing Framework to TDR Testing (Sheet 3 of 4)

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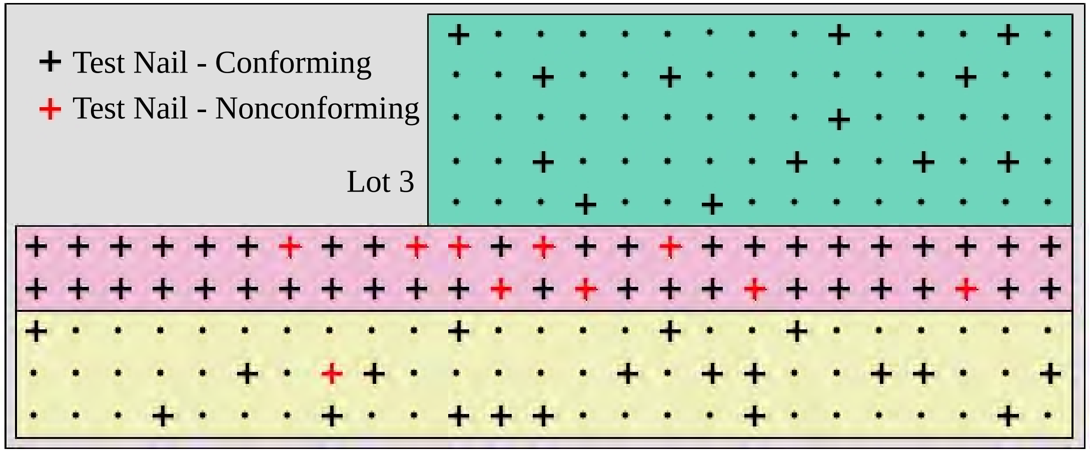
For Lot 3, 13 nails are randomly selected to be tested:



- No nonconforming soil nail is detected
- No. of nonconforming soil nails = Number (0) given in Alert Criterion
- No further action is required for Sample Lot 3

Figure 25 - Application of Proposed Sampling and Testing Framework to TDR Testing (Sheet 4 of 4)

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斜坡岩土工程手冊(1998)，308頁(1984年英文版的中文譯本)。

Highway Slope Manual (2000), 114 p.

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岩土指南第五冊	斜坡維修指南，第三版(2003)，120頁(中文版)。
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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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