INTERIM REPORT ON NON-DESTRUCTIVE TESTS FOR CHECKING THE INTEGRITY OF CEMENT GROUT SLEEVE OF INSTALLED SOIL NAILS

GEO REPORT No. 176

W.M. Cheung & D.O.K. Lo

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

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PREFACE

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

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R.K.S. Chan
Head, Geotechnical Engineering Office
December 2005

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FOREWORD

This report presents the results of a study on identifying and developing potential non-destructive methods for checking the quality of cement grout sleeve in installed soil nails.

In this study, five methods were identified, among which three have been selected for field trials. An assessment of their reliability and accuracy has been conducted. Recommendations are also made for future development.

This study was carried out by Mr W.M. Cheung of Special Projects Division under the supervision of Dr D.O.K. Lo. Much of the site supervision was performed by the technical officers Mr K.C. Chan and Mr K.Y. Wong. Valuable assistance in arranging field trials was provided by Design Division and Landslip Investigation Division. A number of colleagues have provided useful comments on a draft version of this report. All contributions are gratefully acknowledged.

This report is substantially the same as SPR 5/2003. Changes have been made to improve precision in response to comments received on SPR 5/2003, which is hereby superseded.

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ABSTRACT

As part of the development work in enhancing the quality control of soil nail installation works, an in-house project has been conducted by the Geotechnical Engineering Office of Civil Engineering Department to identify and develop practical non-destructive means for checking the integrity of cement grout sleeve.

The study has identified three techniques for field trial. They are the Sonic Echo Method, Surface Wave Time Domain Reflectometry and the Electrical Resistance Method. The findings of the field tests are discussed in the Report.

Based on the study, it is considered that the Electrical Resistance Method has the highest potential for field application. The method is capable of identifying soil nails of significant grouting defects or anomalies. However, the method cannot distinguish explicitly the type of defects, which may be in the forms of grout defect or atypical short reinforcement. Nevertheless, the Electrical Resistance Method looks promising as a quick, convenient and economical means to aid identifying soil nails that have significant grouting defects.

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CONTENTS

1. INTRODUCTION

As part of the development work in enhancing the quality control of soil nail installation, a study has been conducted to identify and develop practical non-destructive means for checking the integrity of cement grout sleeve. Five techniques have been identified and examined. Three of them have been selected for further investigation in the field.

2. REVIEW OF INTERNATIONAL PRACTICE

A review of design and construction guidelines related to soil nailing published by various countries has been carried out. These include standards used in the United States of America (Byrne et al, 1998; Elias & Juran, 1991; Porterfield et al, 1994), the United Kingdom (BSI, 1995 and 2002; Department of Transport, 1994; Murray, 1993), France (French National Research Project, 1991) and Japan (Japan Highway Public Corporation, 1998). None of these documents contain guidelines on non-destructive means for checking the integrity of cement grout sleeve of soil nails.

Information search of technical documents published by universities and research institutes has also been carried out on the Internet. Some non-destructive methods that have potential to check the integrity of grout sleeve have been identified and examined. They include GRANIT® developed by the University of Aberdeen in the United Kingdom, Tomography in conjunction with Cross-hole Logging Method, Sonic Echo Method, Surface Wave Time Domain Reflectometry and Electrical Resistance Method. The working principles of these methods are given below.

2.1 Principle of Non-destructive Methods Identified

2.1.1 GRANIT® Method

The method was originally developed for checking the integrity of ground anchors. The testing system operates by exciting a tensile axial impact to the tendon of the test anchor such that the reflected signal, if any, from the tendon can be detected by an accelerometer mounted at the head of the anchor. The characteristics of the reflected signal is affected by the extent of the free length and the magnitude of the tension in the tendon. The reflected signal is analyzed by a trained artificial neural network (ANN) and the type of defects can then be identified. In order to improve the diagnostic ability of the testing system, the ANN should be trained by sufficient number of reflected signals of different types of known defects. As such, before the technique can be applied to check the integrity of grout sleeve in soil nails, a large amount of data is required (see www.eng.abdn.ac.uk/granit/ for more details).

2.1.2 Tomography in Conjunction with Cross-hole Logging Method

Cross-hole logging is a type of low strain test used to test the integrity of concrete pile. The method requires pre-installation of two plastic tubes parallel to the test pile. The tubes should be situated at the opposite side of the test pile from each other. A signal emitter and a receiver are then inserted into the tubes simultaneously such that the ultrasonic pulse emitted

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will pass through the pile before reaching the receiver. Thus, by analyzing the characteristics of the signal received, one can detect the defects in the pile shaft. In order to improve the accuracy of the analysis, the concept of tomographic imaging has been borrowed. Tomography is a generic term that technically refers to "draw a slice or a section" of a test material. Tomographic imaging in cross-hole logging is the creation of accurate colour-coded images that provide a clear and detailed presentation of the variation of propagation velocity of the emitted signal in the pile shaft such that the capability of differentiating defects can be improved. If the technique is to be applied to check the integrity of grout sleeve in soil nails, drillholes parallel to the soil nails are required.

2.1.3 Sonic Echo (Low-strain Integrity) Method

The principle of this method is similar to that for determining the length of installed steel soil nails (Cheung, 2003). This method involves examining the generation, transmission and reception of an acoustic wave in grout sleeve. The acoustic wave is commonly known as a stress wave or shock wave, which is generated by striking the surface of a grout sleeve with a light hand-held hammer. The generated wave will travel along the grout sleeve until it reaches a section where there is a discontinuity or change in physical properties, and a reflection will occur. The wave will travel forth and back along the grout sleeve leading to the occurrence of successive deformation at the top end surface of the grout sleeve. The amplitude of deformation is a function of time corresponding to the arrival of subsequent reflections until they are damped out. Thus, a number of "deflections" will be detected at the top end surface of a grout sleeve during the test. The time between any two consecutive arrivals of reflections is related to the distance between the surface of grout sleeve and the point of reflection. That is:

$$L = \frac{V_s . t}{2} \qquad \text{..........(1)}$$

where L = length between the surface of grout sleeve and the location where a discontinuity occurs (m)

V_s = velocity of propagation of a stress wave through the grout sleeve (m/s)

t = time lapsed between the initial excitation and the arrival of the reflected stress wave (s)

If the velocity of wave propagation in the grout sleeve is known, one can estimate the length of grout sleeve before the first discontinuity is met. The velocity of wave propagation can be deduced either by calibrating sleeves of known length or by deriving theoretically with the following equation:

$$V_s = \sqrt{\frac{E}{\rho}} \qquad \text{..........(2)}$$

where E = modulus of elasticity of grout (N/m^2)

ρ = density of the grout (kg/m^3)

The velocity of wave propagation in a grout sleeve ranges typically from 3,500 m/s to

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4,000 m/s. Figure 1 illustrates the idealised waveform of a low-strain integrity test with the time elapsed between the initial excitation and arrival of subsequent reflected stress waves with and without damping effect. In reality, reflections would occur at a number of locations where there are changes in the grout homogeneity. In addition, waves of different frequencies would be excited when a hammer is struck on the grout sleeve. As illustrated in Figure 2(a), it can be difficult to identify the time interval between consecutive reflections if the response data are plotted in time domain. To circumvent this problem, one may plot the same set of data in frequency domain as in Figure 2(b). In this case, the dominant frequency (f) corresponds to a particular standing wave could be identified. A particular wave with a wavelength of L/2, L, 2L, etc will form a standing wave inside the grout sleeve, leading to the occurrence of the dominant frequency. If the velocity of wave propagation V_s is known, one can determine the length of a grout sleeve by the following expression:

$$L = \frac{V_s}{2f_{low}} \quad \text{...(3)}$$

where f_{low} = lowest dominant frequency (Hz)

2.1.4 Surface Wave Time Domain Reflectometry

Time Domain Reflectometry was first developed in the 1950s to detect faults in transmission cables (O'Connor & Dowding, 1999). When an electrical pulse is sent along a pair of closely placed conductors, changes in impedance along the pair would cause reflections. The characteristics of a reflection, such as its strength and polarity relative to the source signal, depend on the nature of the change in impedance. The time lapsed between the source and the reflection signals can be used to determine the location of the reflection if the transmission velocity of the signal is known.

Surface wave time domain reflectometry works on a single conductor. When a signal is sent down a conductor, reflections occur where there are changes in impedance of the conductor, which depends in part on the dielectric property of the material surrounding it. In a grouted nail, sound grout and various forms of defective grout possess different ranges of dielectric values. The reflection signals from a surface wave time domain reflectometry test on the nail could in principle be interpreted for the location and nature of grout defects. Supreme Instruments Ltd (2003) provides a qualitative description of the concept of result interpretation. The concept is summarised in Figure 3.

2.1.5 Electrical Resistance Method

The electrical conduction in a steel reinforcement is by means of a flow of free electrons whereas that in ground or grout sleeve is by a flow of mobile ions. If an electrical current is caused to flow from an installed steel soil nail through the ground to a remote current electrode, one can measure the total electrical resistance between these two contact points. As illustrated in Figure 4, the total electrical resistance R_{total} is composed of the following four components:

$$R_{total} = R_s + R_c + R_r + R_g \quad \text{..(4)}$$

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where R_s = resistance of the steel reinforcement, the remote current electrode and the connecting leads (Ω)

R_c = contact resistance at the conduction mode interfaces between the steel reinforcement and the grout sleeve, and between the remote current electrode and the ground (Ω)

R_r = radial resistance across the grout sleeve (Ω)

R_g = resistance of the ground between the soil nail and the remote current electrode (Ω)

The conductor resistance, R_s, is effectively negligible in comparison to the other components.

The contact resistance, R_c, is attributed to the change of the conduction mode from a flow of free electrons to a flow of mobile ions at the interface between a steel reinforcement and the grout sleeve enclosing it, and that between the remote current electrode and the ground in contact. This component is relatively small.

The radial resistance, R_r, is attributed to the electrical resistance in the grout sleeve, which is a function of the inner and outer radii of the grout sleeve and the ionic mobility within the grout. For an intact grout sleeve, the radial resistance increases non-linearly as the sleeve radius increases and decreases reciprocally as the length increases.

Ground resistance, R_g, is attributed to the electrical resistance of the ground between the soil nail and the remote current electrode. Fundamentally it is variable and its value depends on a number of parameters such as the moisture content of the ground, the ionic conductivity of the groundwater and the clay content. Variation in this property reflects the inherent heterogeneity of the local geology. However, if the remote current electrode is implanted adequately far from the soil nail, this variation would be attributable to a large hemispherical volume of soil mass around the soil nail. This means that for a given localised area, such as at a particular row of soil nails, the ground resistance should vary smoothly from test point to test point.

Figure 5 illustrates the set-up of the test. An alternating current (AC) is applied between the soil nail and the electric current electrode to avoid possible polarisation of the electrode and soil nail. The electrical potential in the ground is inversely proportional to the distance from the soil nail or the electric current electrode. Resistance associated with the remote current electrode can effectively be eliminated from this resistance sum (R_{total}) by placing an intermediate potential electrode between the soil nail and the remote current electrode, to measure the potential difference from the installed soil nail. It is because the change in the electrical potential in the vicinity of the potential electrode is small when compared with that close to the soil nail. The technique is typically used for earthing resistance measurement of electric power installations. The elements of the Equation (4) can then be redefined as:

R_s = resistance of the steel reinforcement and the connecting lead (Ω)

R_c = contact resistance at the conduction mode interface between the steel reinforcement and the grout sleeve (Ω)

R_r = radial resistance across the grout sleeve (Ω)

R_g = resistance through the approximate hemisphere of ground between the soil nail and the potential electrode (Ω)

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The greatest part of the ground resistance R_g occurs within the close radial vicinity of the soil nail and the R_{total} deduced using an intermediate potential electrode is a measure of the resistance associated mainly with the soil nail and the surrounding ground, which depends on the dimensions and resistivity of the grout sleeve.

The spatial variation of the total electrical resistance of soil nails can serve as an indicator for checking the integrity of the grout sleeve. If the total electrical resistance measured at a soil nail is found to be significantly different from those of the adjacent soil nails of the same configuration, there is a high probability that the soil nail is anomalous. If the total electrical resistance of a soil nail is significantly higher than those in adjacent nails, this would suggest that there may be defects in the forms of voids or discontinuities inside the grout sleeve, atypical short nail length or both types of defects. On the contrary, if the total electrical resistance is significantly lower than those of adjacent nails, it is likely that the contact surface area between the grout sleeve and the ground is comparatively larger than that of the adjacent nails. This could be attributed to the grout loss during soil nail installation works resulting in the formation of a grout bath, bulb or sheet around the steel reinforcement. Once the spatial variation of the total electrical resistance is established, an initial screening of the characteristics of the installed soil nail and hence its integrity can be carried out.

Figure 6 depicts the anticipated results of the test for soil nails with and without anomalies in the grout sleeve.

3. SITE TRIALS

3.1 Phase I Site Trial

3.1.1 General

Based on the literature review, three of the identified techniques viz. the Sonic Echo Method, Surface Wave Time Domain Reflectometry, and the Electrical Resistance Method were selected for the Phase I site trial at a site in Tuen Mun. The trial included the testing of eight prefabricated soil nails, some working soil nails and some nails which were installed for pull-out tests. The prefabricated soil nails were 10 m long with artificial grout 'defects' as shown in Figure 7 and Plate 1. They were buried at a depth of 0.15 m below ground. The working nails and the 'pull-out test' nails were 17 m long. The former were fully grouted while the latter were grouted for about 2 m at the far end. The 'defect' configuration of the prefabricated nails and the grout location of the pull-out test nails were made known to the parties taking part in the trials, to make it easier for them to calibrate and demonstrate their methods.

3.1.2 Sonic Echo (Low-strain Integrity) Method

The method took less than half an hour for one test. The instrument required for the test is readily available in the market (see Plate 2). However, the method required experienced personnel to conduct the test and to interpret the results. In this trial, no meaningful interpretation of the test results could be carried out because there were considerable difficulties in identifying the reflection of the stress wave from the discontinuities of grout sleeve and the lowest dominant frequency from the results. This could be attributed to the relatively rapid decay in the signal intensity and the influence from

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the activities nearby.

3.1.3 Surface Wave Time Domain Reflectometry

This method is quick and it only takes a few minutes to conduct a test. The instrument used is shown in Plate 3; it was designed and constructed by Supreme Instruments Ltd. The company adjusted the instrument halfway through the field trial.

Supreme Instruments Ltd (2003) recorded the test results and used them to deduce location of the grout defects. An important step of the process was identifying the parts of the signal that corresponded to reflection from the grout defect boundaries. The defect locations were then calculated using a combination of inferred and assumed signal velocity values. The test results and the deductions have been reproduced in Figures 8 and 9. As can be seen from the figures, use of the test results relied heavily on interpretation.

3.1.4 Electrical Resistance Method

This method is quick and it only takes a few minutes to conduct a test. The instrument required for the test is readily available in the local market (see Plate 4). This method does not require particular expertise in conducting the test and in interpreting the test results.

Table 1 summarises the test results on the eight prefabricated soil nails. As indicated in the results, soil nails with the longest grout length (i.e. soil nail nos. 4 and 8) have the lowest total electrical resistance when compared with other soil nails of the same reinforcement length but shorter grout length. This validates the assumption that the total electrical resistance decreases as the length of grout sleeve increases.

For soil nails with the same length of grout sleeve, those with the portion of exposed reinforcement surrounded by soil (i.e. soil nail nos. 5, 6 and 7) have lower total electrical resistance than those exposed to air (i.e. soil nail nos. 1, 2 and 3). This means that the variation of total electrical resistance depends on the type of material encasing the steel reinforcement. The contrast between air and grout in terms of electrical resistance is greater than that between soil and grout. In other words, it would be relatively easier to identify those soil nails with grout discontinuities filled by air than by soil.

Additional tests were carried out on working nails and nails installed for pull-out tests at the site. Figure 10 shows the locations of these nails in row BI and BL. The test results are shown in Figures 11 and 12. All the nails tested were 17 m long. The test results indicate that the values of the total electrical resistance of the soil nails of a given configuration situated along the same row vary gradually. This gradual variation of total electrical resistance is mainly due to the inherent changes in conductivity of the ground. There are local spikes of total electrical resistance at individual soil nails, e.g. P44 and P52 in row BI (see Figure 11(a)), and P38 in row BL (see Figure 12(a)). They are in fact soil nails used for pull-out test. These nails have a grout sleeve of only 2 m long at their far ends compared with the 17 m long grout sleeves of the adjacent working soil nails. The local spikes represent significant increases in the total electrical resistance of these nails and indicate that electrical resistance is a promising indicator for identifying soil nails with significant grout defects.

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The beauty of this testing method is that one could identify soil nails with significant grout defects by visual examination of the raw measurement data plots. Apart from that, one may use statistical methods to assist in identifying outliers. For example, the variation of total electrical resistance can be fitted by a curve (e.g. polynomial) through regression analysis. This represents the inherent variation of the spatial mean of total electrical resistance in the ground. If the difference between the measured and the estimated spatial mean of total electrical resistance, herein referred as the residual resistance, is plotted against the spatial location of the soil nails, it would fluctuate about the line of zero resistance as shown in Figures 11(b) and 12(b). If sufficient data are available, one may also determine the standard deviation σ of the residual resistance and define a band of expected variation about the zero resistance line. This band of expected variation should be defined in such a way to reflect the uncertainty for a normal grouting operation. Any measurements outside this band of expected variation can be considered as outliers. For illustrative purpose, a band of $\pm 3\sigma$ (corresponds to a chance of 99.7% of falling into the band if normal distribution is assumed) is plotted in Figures 11(b) and 12(b). Similar to that observed from the raw measurements, the residual resistance of soil nails P38, P44 and P52 with shorter grout sleeve (2 m c.f. 17 m) are offset considerately from the line of zero resistance and lie outside the band of $\pm 3\sigma$. The residual resistance of working soil nails along row BI is generally less than 5 Ω, compared with 25 Ω and 20 Ω at P44 and P52 respectively. Similarly, the residual resistance of working soil nails along row BL is generally less than 10 Ω, whereas that of P38 is about 70 Ω. This indicates that soil nails of shorter grout sleeve ("pull-out test" nails) can be differentiated from the adjacent soil nails by way of statistical outliers.

It is interesting to note in Figure 12 that the total electrical resistance of "pull-out test" nail P39 was comparable to that of the adjacent working soil nails. This is because at the time of testing, the void section had already been grouted up. The documentation and interpretation of the test results is given in Cosine Ltd (2003).

3.2 Phase II Site Trial

Recognizing the potential of using the Electrical Resistance Method to identify soil nails with significant deficiency in grout integrity, a more extensive site trial using this method has been carried out at another site in Tai Po. The objective of this trial is to determine the sensitivity of the method with respect to the extent of grout discontinuities and to establish criteria for identifying outlier in terms of residual resistance. Plate 5 shows the use of the Electrical Resistance Method at the site. Appendix A outlines the procedure of the test.

More than 70 soil nails of various lengths have been tested and their locations are shown in Figure 13. Soil nails for pull-out tests have been grouted in three stages in order to obtain more measurements on nails with various lengths of grout sleeve. Some of the test results are presented in Figures 14 to 17. Similar to those revealed in the Phase I trial, soil nails of significantly different lengths of grout sleeve can be differentiated by this method. For example, the measurement data of soil nails in row 6 shown in Figure 14(a) indicate that the total electrical resistance for 15 m long working nails (fully grouted) varies smoothly in the spatial domain. On the contrary, soil nail of shorter grout sleeve such as nail P4 (45.8 Ω when grout sleeve length is 2.4 m) can easily be differentiated from the adjacent 15 m long soil nails (18.4 Ω at nail R6.4 and 17.9 Ω at R6.5). When nail P4 was gradually

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grouted up from 2.4 m to 10.5 m, the total electrical resistance was reduced correspondingly from 45.8 Ω to 22.6 Ω (i.e. a reduction of 23.2 Ω for an increase of 8.1 m grout sleeve). However, when P4 was further grouted up from 10.5 m to 15 m (i.e. fully grouted), the total electrical resistance became 20.8 Ω (i.e. a reduction of 1.8 Ω for an increase of 4.5 m grout sleeve). This means that the sensitivity of the test decreases as the length of the grout sleeve increases.

The test results of soil nails in row 8 in Figure 15(a) indicate that nails of grout sleeve length of 2 m, 7 m and 9 m can be differentiated from those of 15 m in length. The method is also capable of distinctly differentiating "pull-out test" nail P6 from the adjacent working nails when the grout sleeve was 2 m long. When "pull-out test" nail P6 was grouted up to 15 m long, the total electrical resistance became comparable to those at the adjacent working nails. Using the statistical method shown in Figure 15(b), one can marginally recognise the "pull-out test" nail P6 as a statistical outlier when the grout sleeve was 8.5 m long. Soil nail R8X12 also seems to be a statistical outlier. Examination of the drilling, grouting and supervision records did not identify any anomaly. The test result is therefore not conclusive. One may also observe that working nails with 7 m grout sleeve can be differentiated from those adjacent nails of 9 m long.

Similarly, the test results for soil nails in row 9 and row 7 are shown in Figures 16 and 17 respectively. The smooth spatial variation of the total electrical resistance for the 9 m long soil nails in row 9 suggests that the grout integrity is broadly similar among the soil nails. Figure 17 indicates that when the length of the grout sleeve of nail P5 was increased gradually from 3 m to 15 m, the total electrical resistance of the nail decreased correspondingly. During the first stage of re-grouting (i.e. from 3 m to 8 m), the decrease in total electrical resistance is about 1 Ω. The reduction after the second stage of re-grouting (i.e. from 8 m to 15 m) is also about 1 Ω although the grout sleeve has been increased by 7 m long. This rate of decrease in electrical resistance is relatively lower than those revealed at other soil nails for pull-out tests. Apart from the low rate of decrease, the total electrical resistance of the nail when the grout sleeve was 3 m long was noted to be even lower than those measured for the adjacent nails of 7 m and 9 m long. This indicates that the amount of grout in nail P5 could be larger than that expected. Indeed, the grouting records for nail P5 indicated that the actual volume of grout was five times more than the theoretical volume of the drillhole, whereas the ratio was about 1.5 to 2 for other working and "pull-out" nails at the site. This means that a grout bulb might have been formed in the vicinity of the soil nail, P5, resulting in lower total electrical resistance.

During the Phase II site trial, some measurements have been collected on both sunny and raining days. The objective of collecting these measurements is to examine if the method is weather-dependent. The measurements, shown in Table 2, indicate that the total electrical resistance will be reduced if the measurement is taken under rainy condition. The reduction will be in an order of a few percents only if the grout sleeve is intact. In contrast, if there is substantial void section in a grout sleeve such as nails P1 to P5, the reduction in electrical resistance would be substantial (e.g. 13.6% in nail P2). Indeed, these void sections have been probed on the day of measurement and were found to be filled with rainwater. This results in an increase of the conductivity of the soil nail and hence a reduction in the electrical resistance. Thus, the electrical resistance measured at soil nails with intact grout sleeve would be less sensitive to different weather conditions than those with significant grout defects.

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4. DISCUSSION

The results of the three non-destructive methods (Sonic Echo Method, Surface Wave Time Domain Reflectometry and Electrical Resistance Method) for checking the integrity of grout sleeve in installed soil nails have been presented. The trial indicated that the Sonic Echo Method did not work in field application. This method is considered not usable until there is further improvement for application. Surface Wave Time Domain Reflectometry is a quick testing method. It has potential for identifying defects of grout sleeve in installed soil nails. Work is needed to further develop its potential.

Electrical Resistance Method is quick and easy to carry out. It is capable of identifying installed soil nails that have major grout integrity problem by singling themselves out as outliers from the adjacent nails of the same length and diameter. The instrument required for the test is readily available in the local market and there is no particular requirement on expertise of conducting the test or interpreting the test results beyond adherence to the correct procedures. The method, however, cannot explicitly distinguish between defect due to short grout sleeve and that due to short steel reinforcement. To determine the type of defects, one would have to supplement the Electrical Resistance Method by other means to determine the length of steel reinforcement, e.g., Cheung (2003). Also, if all the soil nails tested are of the same quality (e.g. equally bad), there may not be any outliers although the large standard deviation may indicate some problems. Nonetheless, the method looks promising as an aid to screen the quality of soil nail installation works. Further study on the use of the method is recommended, particularly on nails with known or controlled grout defects.

5. CONCLUSIONS

From the trials of using the various methods to check the integrity of grout sleeve, it is considered that the Electrical Resistance Method has the highest potential for field application. The sensitivity of the method depends on the length of the grout sleeve. Based on the available data, the method is capable of differentiating grout sleeves with significant deficiency. The method, however, cannot distinguish explicitly the type of defect, which may be in the forms of grout defect or atypical short reinforcement. The test results for nails with some but not significant defects may not be conclusive. Despite the foregoing, the Electrical Resistance Method looks promising as a quick, convenient and economical means to aid identifying soil nails that have significant grouting defects.

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Table 1 - Test Results on Prefabricated Soil Nails Using Electrical Resistance Method

Test Nail	Length of Grout Sleeve (m)	Length of Void (m)	Length of Soil Sleeve (m)	Total Length (m)	Total Resistance (Ω)	Total Resistance per unit Length of Soil Nail (Ω/m)
1	5.0	5.0	-	10.0	56.9	5.7
2	5.0	5.0	-	10.0	58.3	5.8
3	5.0	5.0	-	10.0	53.5	5.4
4	9.0	1.0	-	10.0	45.7	4.6
5	5.0	0.5	4.5	10.0	50.0	5.0
6	5.0	0.5	4.5	10.0	50.5	5.1
7	5.0	0.5	4.5	10.0	50.2	5.0
8	9.0	0.1	0.9	10.0	47.3	4.7

Table 2 - Measurements Recorded on Sunny and Rainy Days

Soil Nail No.	Length of Grout Sleeve (m)	Length of Void Section (m)	Total Electrical Resistance Measured on Sunny Day (Ω)	Total Electrical Resistance Measured on Rainy Day (Ω)	Reduction in Total Electrical Resistance due to Rain Water (%)
P1	8.1	6.9	33.9	32.7	3.5
P2	8.3	6.7	22.0	19.0	13.6
P3	9.5	5.5	16.3	15.1	7.4
P4	10.5	9.5	23.9	22.3	6.7
P5	8	7.0	16.5	16.2	1.8
R8Y2	9	0	24.5	23.8	2.9
R8Y3	9	0	22.1	21.5	2.7
R8Y4	9	0	22.7	22.2	2.2
R8Y5	9	0	22.1	21.5	2.7

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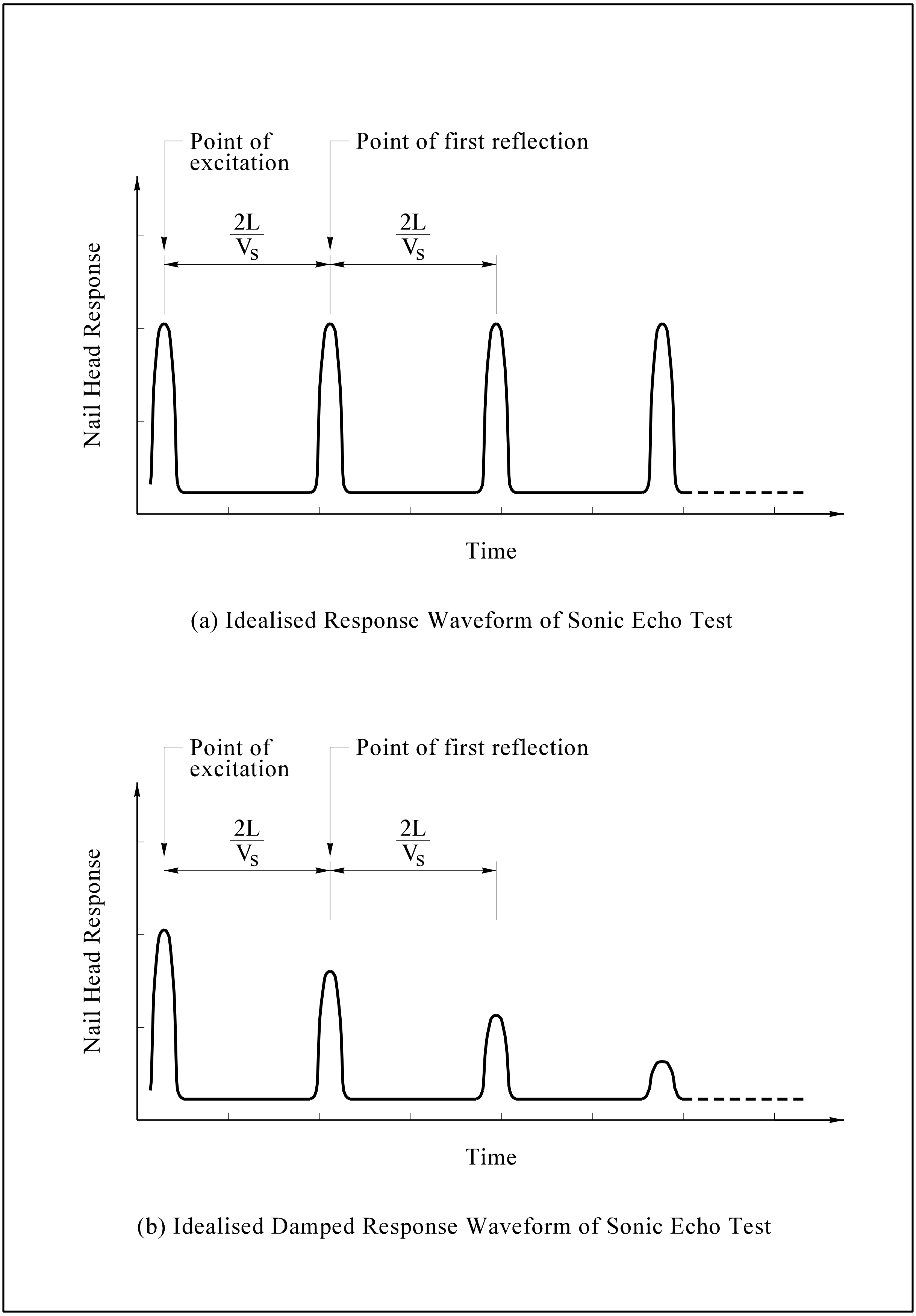

Figure 1 - Idealised Response Waveform of Sonic Echo Test

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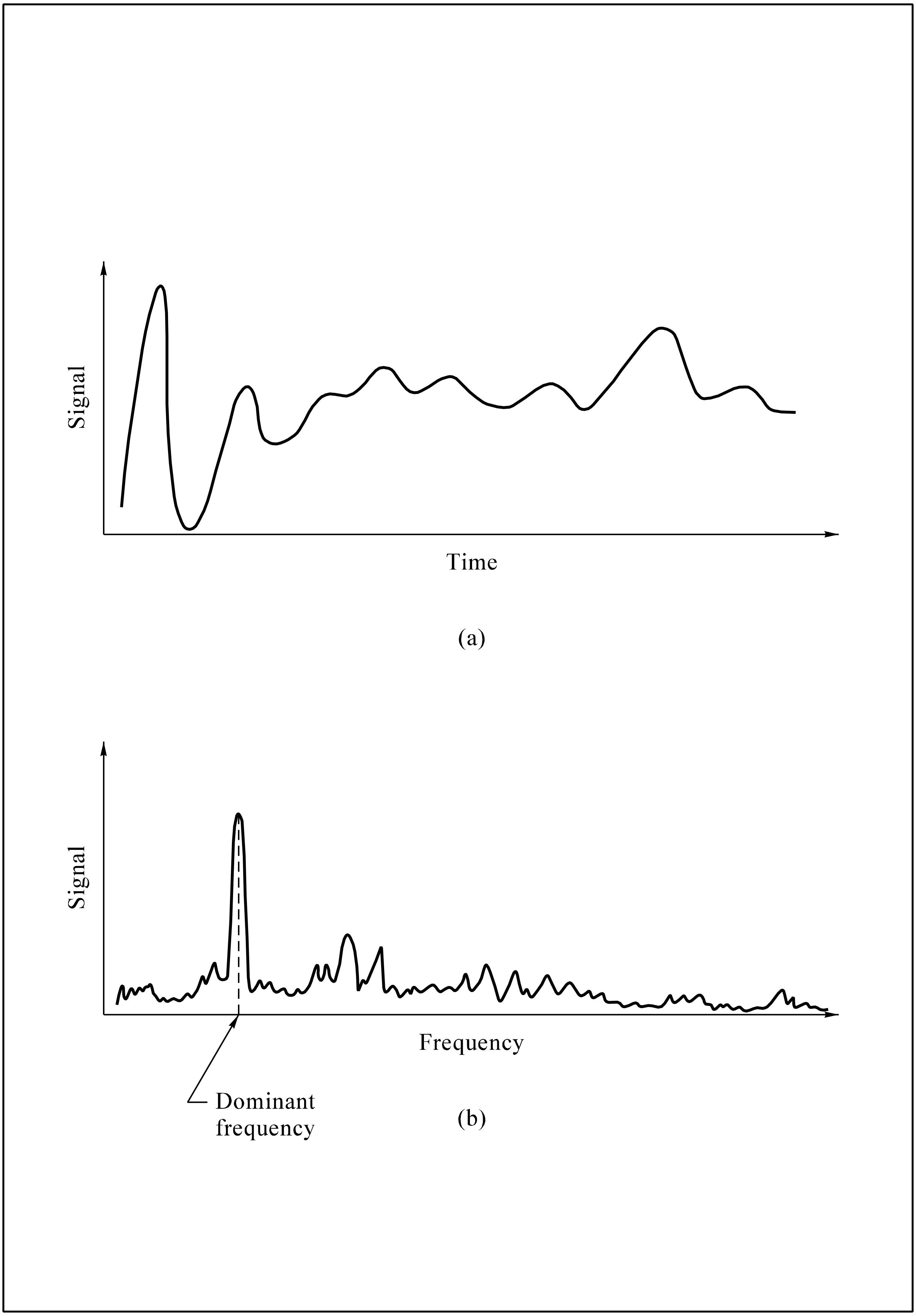

Figure 2 - Response Waveform of Sonic Echo Test

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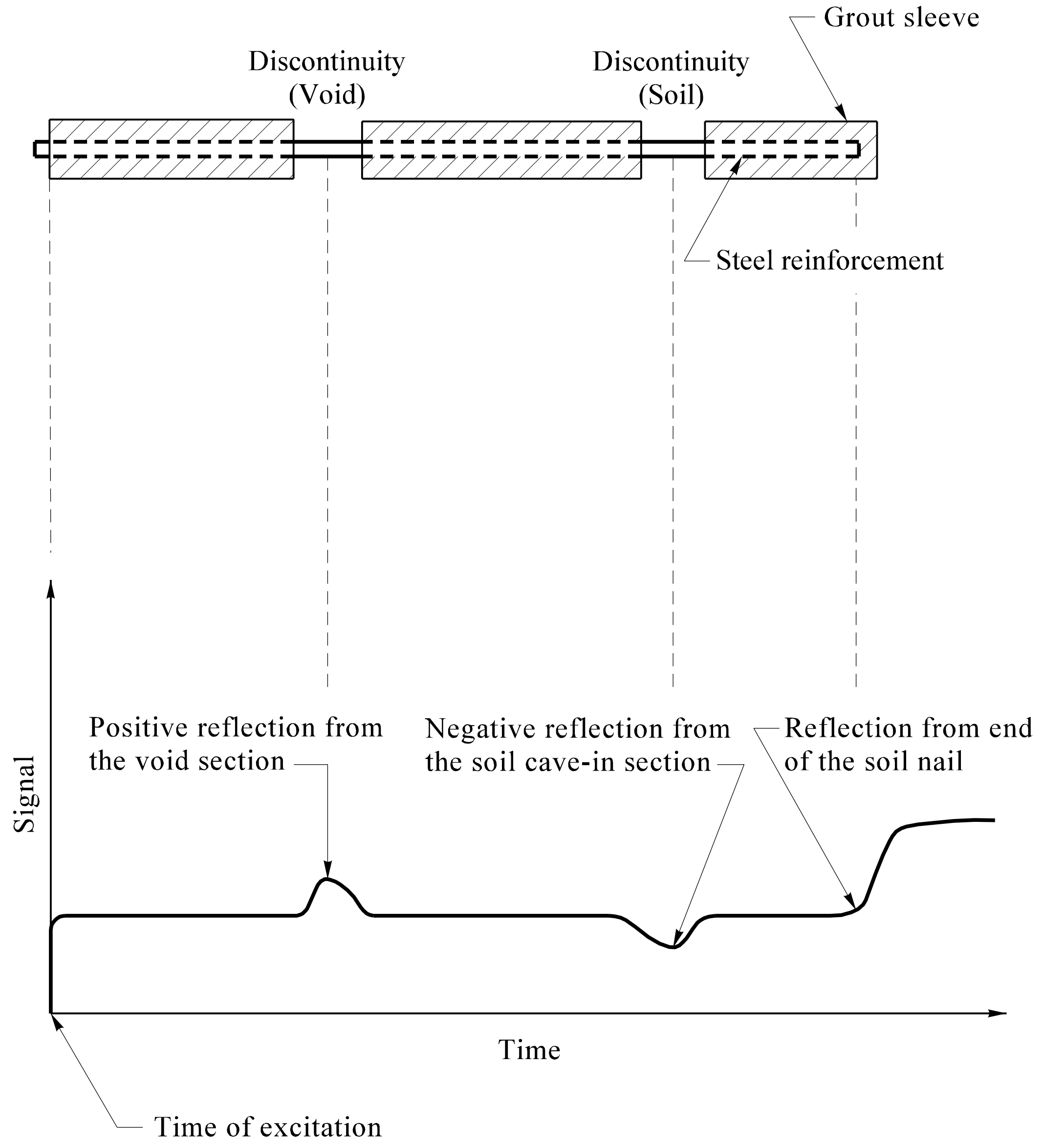

Figure 3 - Schematic Diagram of Idealised Surface Wave Time Domain Reflectometry Signal Response for a Soil Nail with Different Types of Defect (adapted from Supreme Instruments Ltd, 2003)

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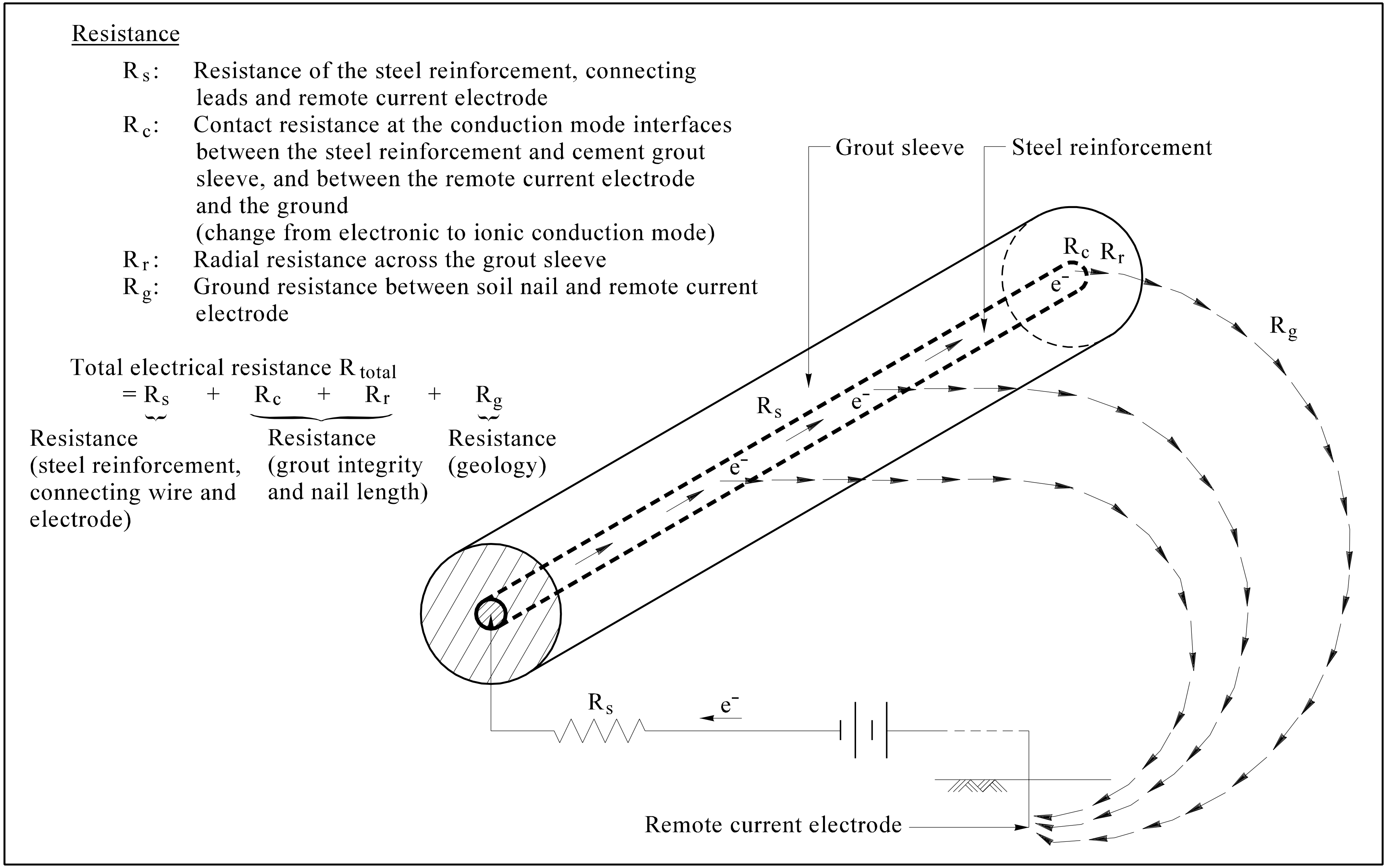

Figure 4 - Components of Electrical Resistance of an Installed Steel Soil Nail

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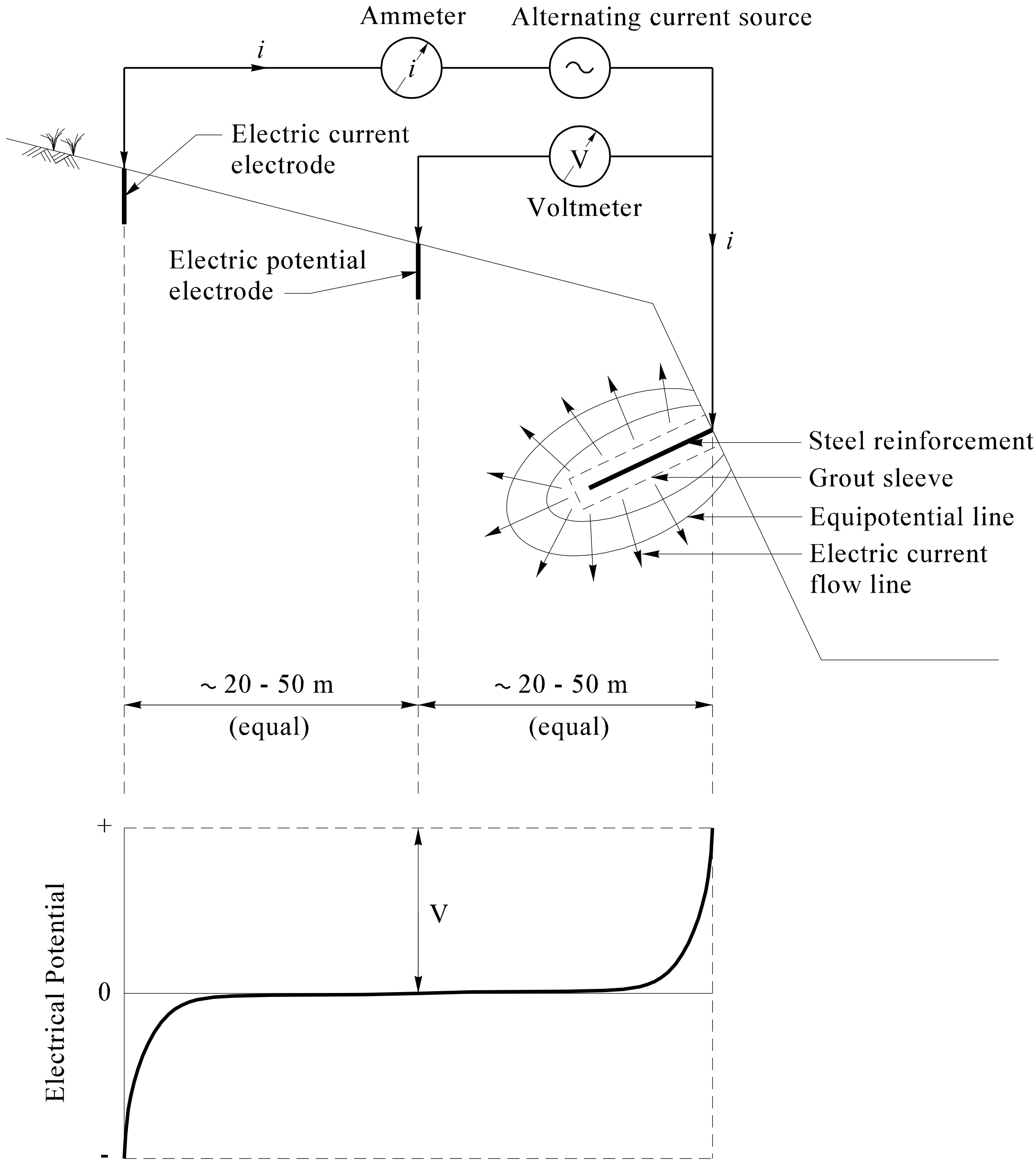
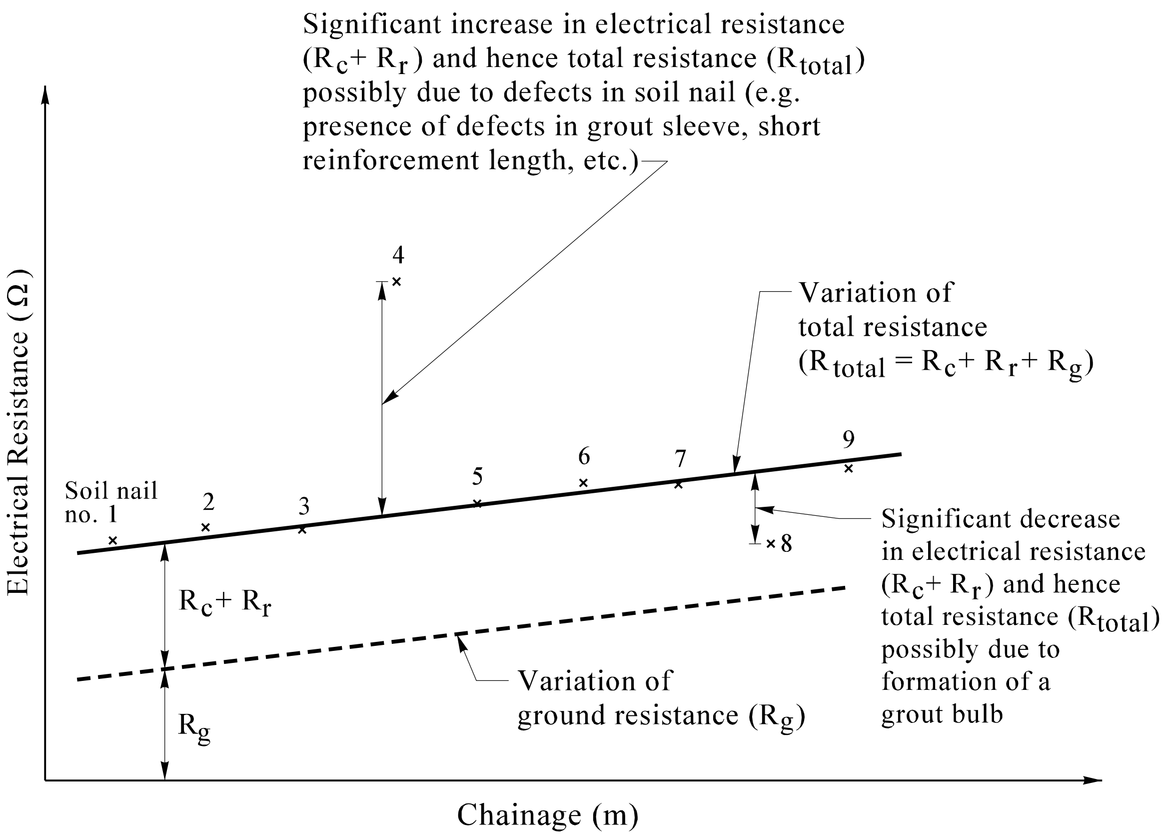


Note: $R_{total} = \frac{V}{i}$

where R_{total} is the total electrical resistance associated with the soil nail and the ground between the soil nail and the electric potential electrode (ohm)

V and i are voltage (volt) and current (ampere) respectively

Figure 5 - Set-up of Electrical Resistance Method



Note: Resistance R_s is negligible when compared with R_c+ R_r+ R_g

Figure 6 - Schematic Presentation of Typical Results Obtained Using Electrical Resistance Method

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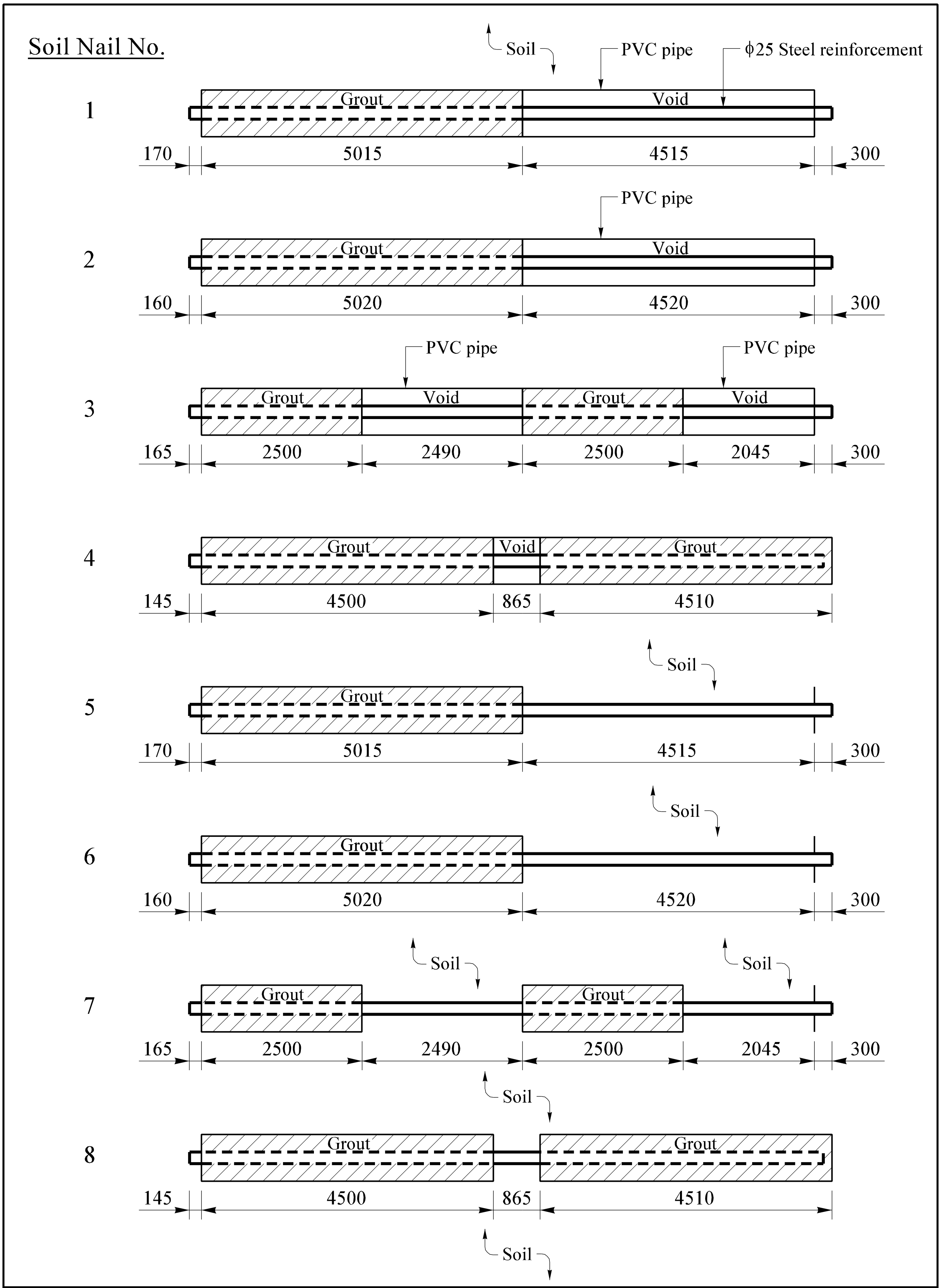

Note: Unit in mm.

Figure 7 - Configuration of Prefabricated Soil Nails

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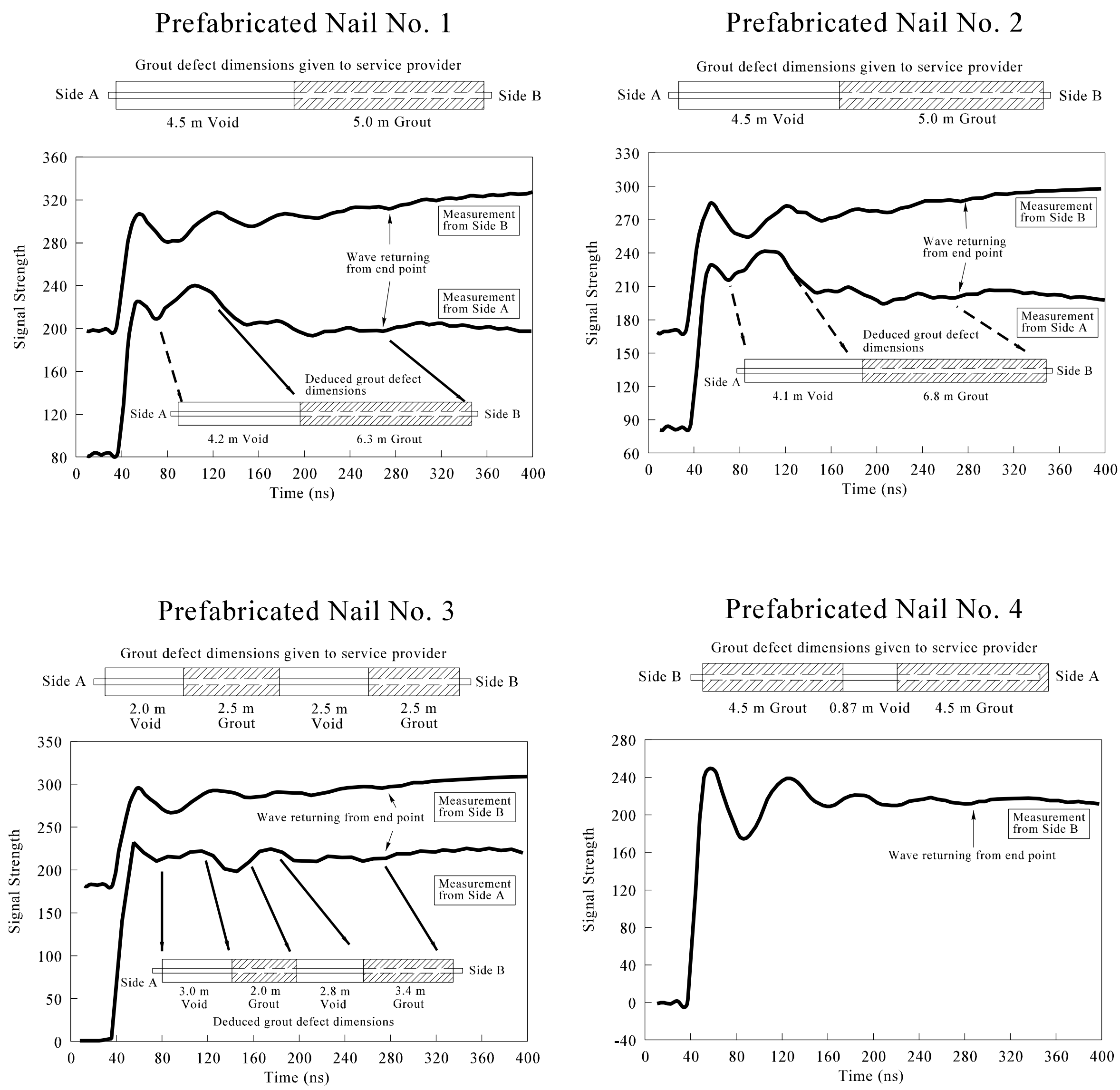

Notes: (1) This set of test results was taken before adjustment of instrument.
(2) Reflection from grout and grout defect boundaries as interpreted in Supreme Instruments Ltd (2003).

Figure 8 - Test Results on Prefabricated Soil Nails Using Surface Wave Time Domain Reflectometry (Sheet 1 of 3)

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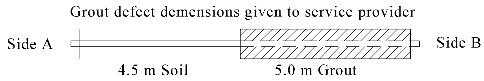
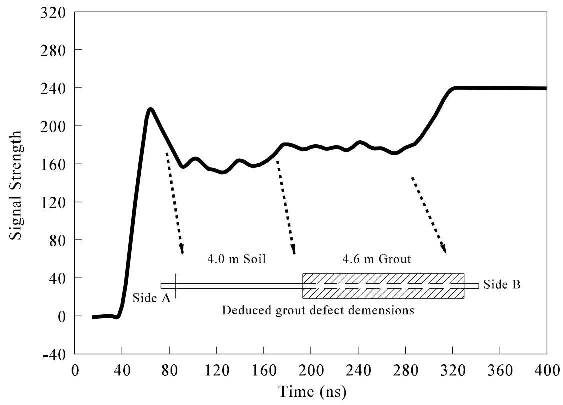
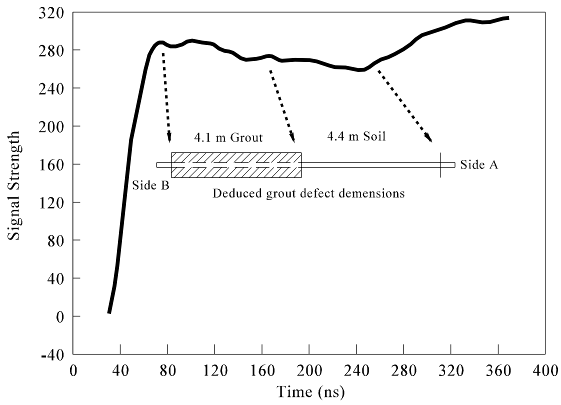
Prefabricated Nail No. 5



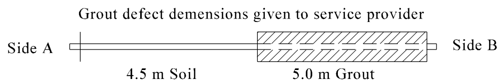
(Measurement from Side A)



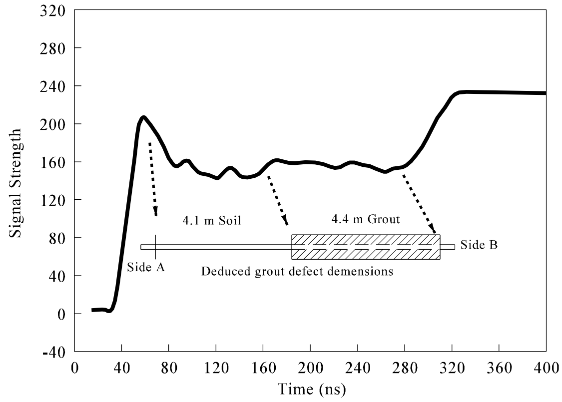
(Measurement from Side B)



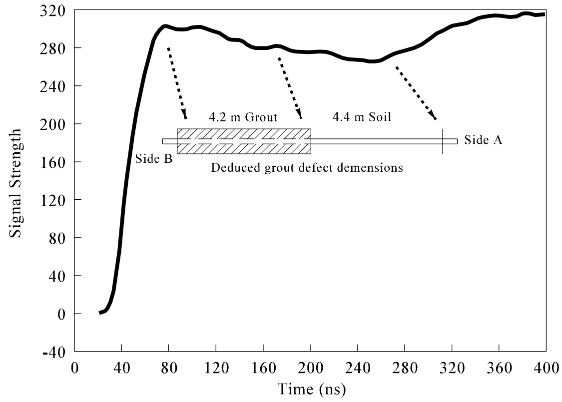
Prefabricated Nail No. 6



(Measurement from Side A)



(Measurement from Side B)



Notes: (1) This set of test results was taken after adjustment of instrument.
(2) Reflection from grout and grout defect boundaries as interpreted in Supreme Instruments Ltd (2003).

Figure 8 - Test Results on Prefabricated Soil Nails Using Surface Wave Time Domain Reflectometry (Sheet 2 of 3)

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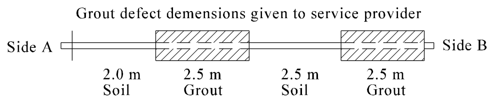
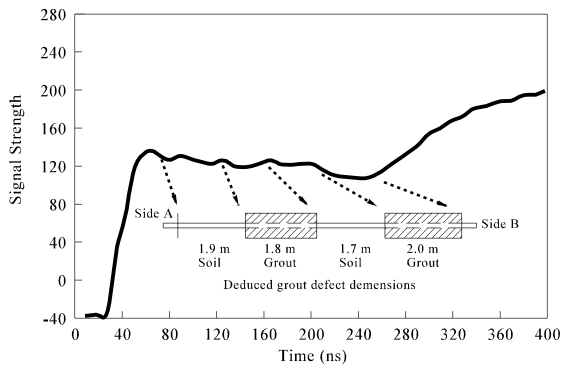
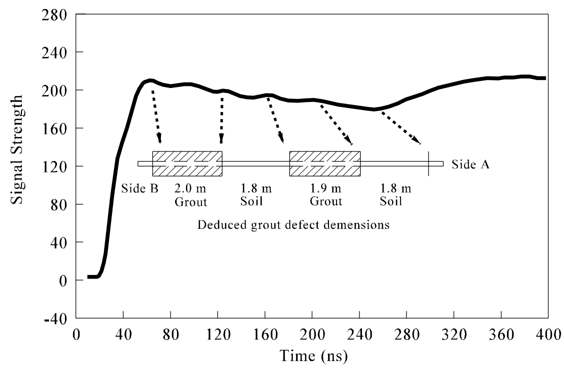
Prefabricated Nail No. 7



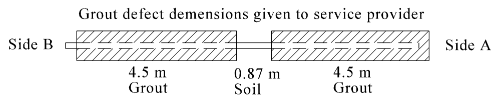
(Measurement from Side A)



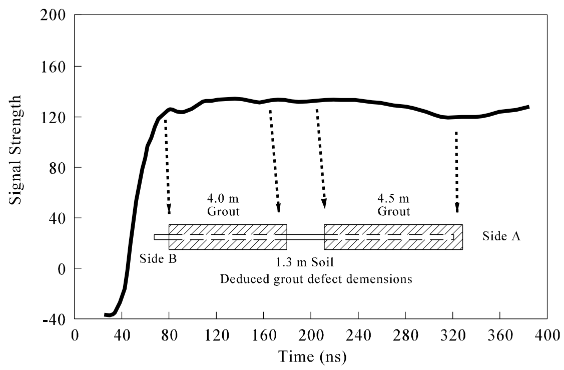
(Measurement from Side B)



Prefabricated Nail No. 8



(Measurement from Side B)



Notes: (1) This set of test results was taken after adjustment of instrument.
(2) Reflection from grout and grout defect boundaries as interpreted in Supreme Instruments Ltd (2003).

Figure 8 - Test Results on Prefabricated Soil Nails Using Surface Wave Time Domain Reflectometry (Sheet 3 of 3)

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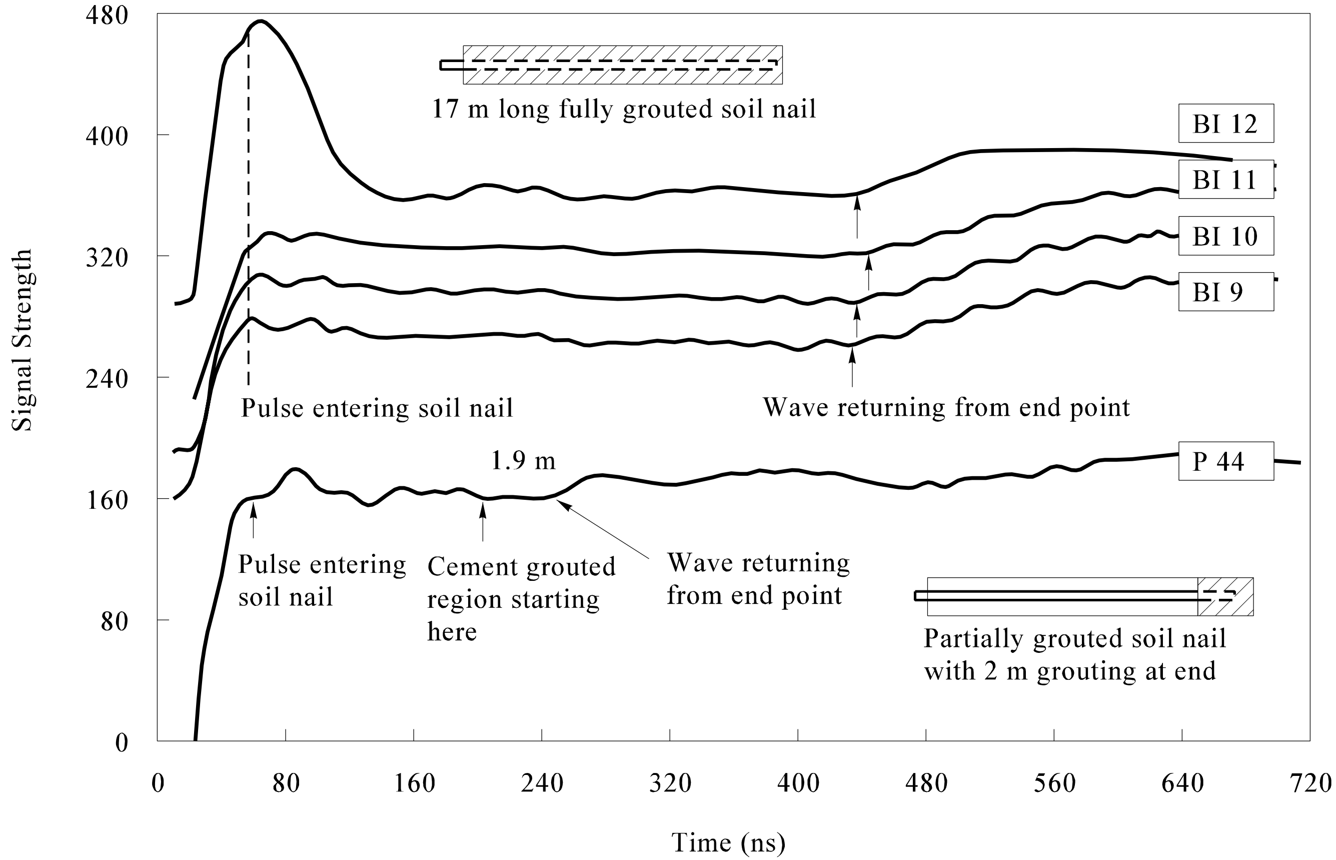


Notes: (1) This set of test results was taken after adjustment of instrument.
(2) Results reproduced from Supreme Instruments Ltd (2003).

Figure 9 - Test Results on Working and "Pull-out Test" Soil Nails Using Surface Wave Time Domain Reflectometry

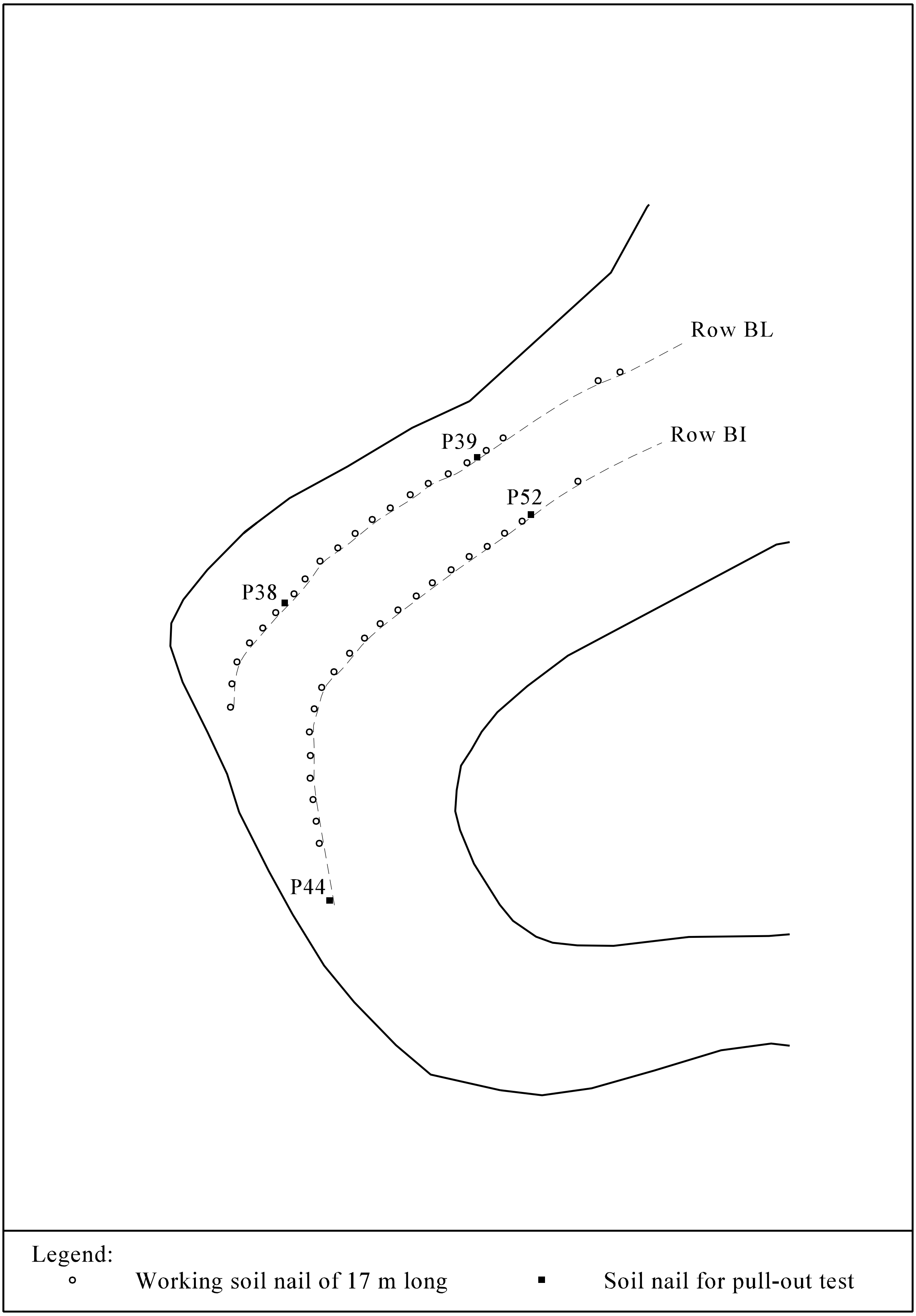
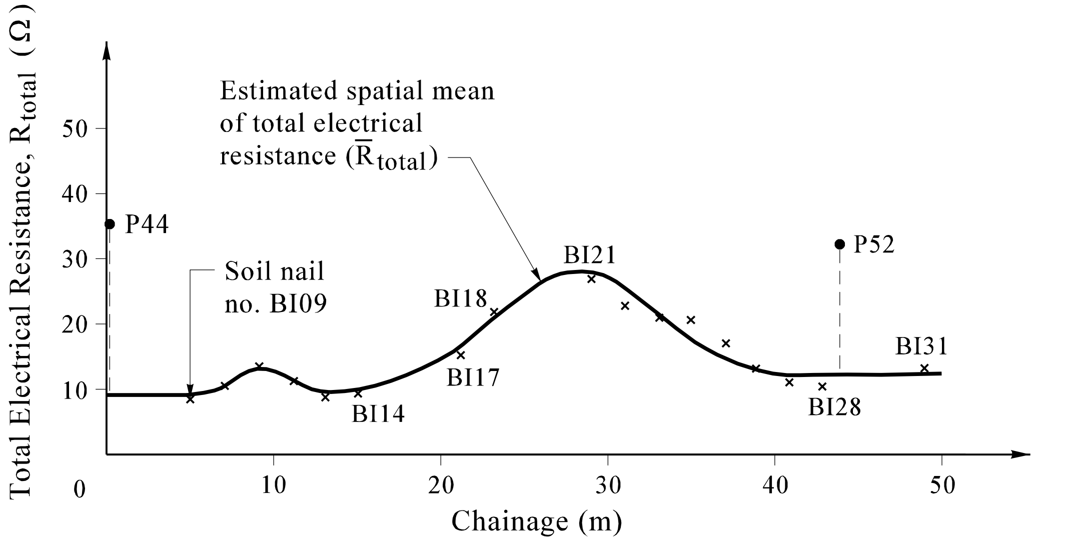
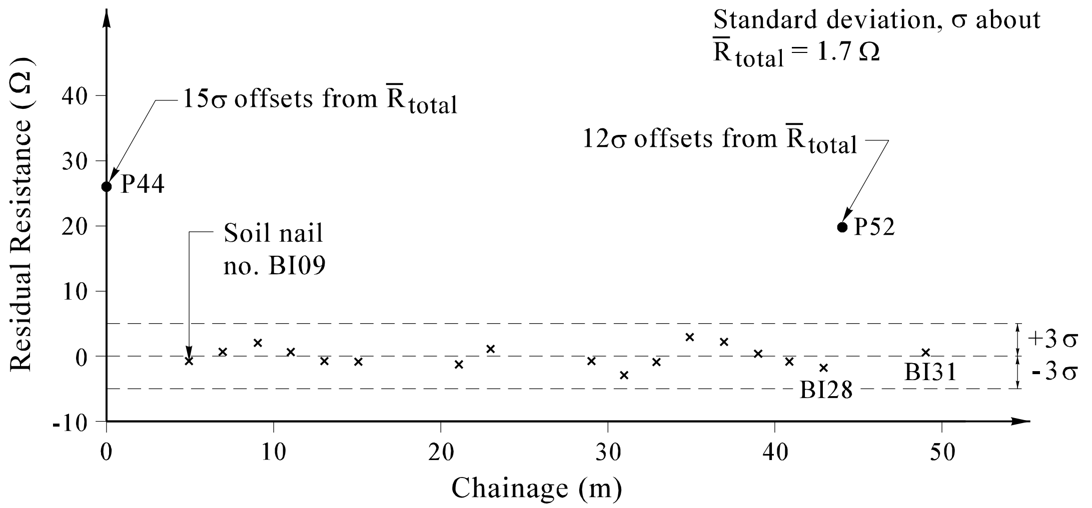


Figure 10 - Location of Test Nails in Phase I Site Trial



(a) Measured Total Electrical Resistance



(b) Residual Resistance

Legend:

× 17 m long grout sleeve • 2 m long grout sleeve

Notes: Residual Resistance = Measured Total Resistance - Estimated Spatial Mean of Total Resistance

$$\text{Standard Deviation, } \sigma = \sqrt{\frac{\Sigma \text{ Residual Resistance}^2}{\text{Number of Measurement}}}$$

Figure 11 - Test Results of Soil Nails in Row BI in Phase I Site Trial Using Electrical Resistance Method

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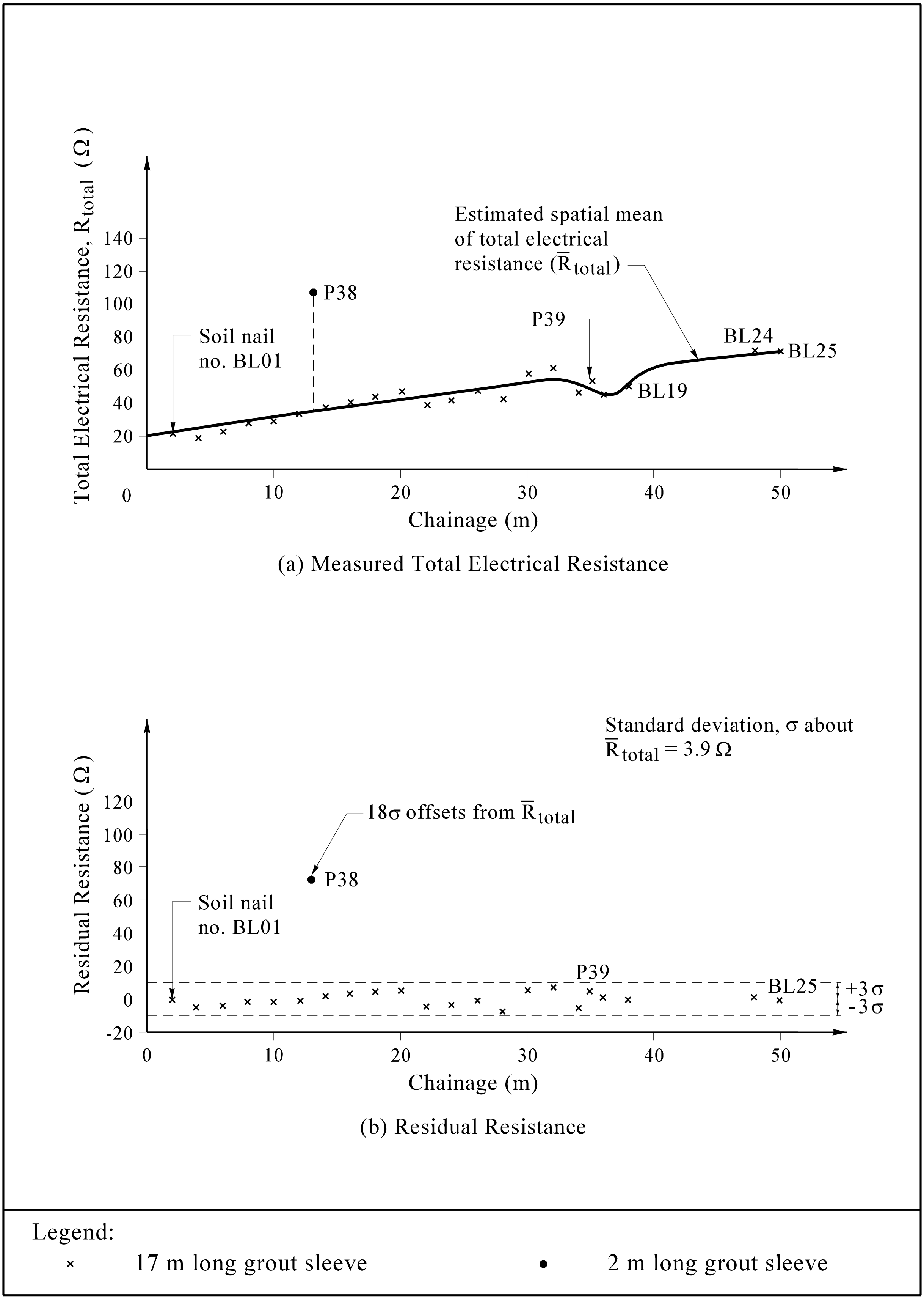

Figure 12 - Test Results of Soil Nails in Row BL in Phase I Site Trial Using Electrical Resistance Method

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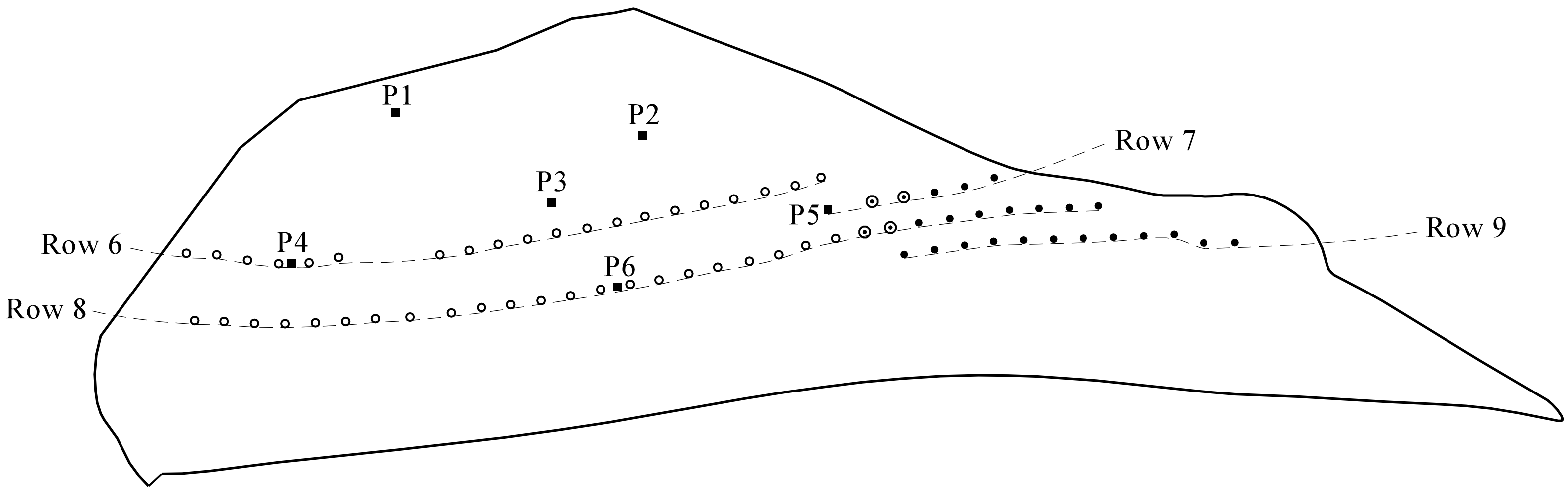

Legend:

○ Working soil nail of 15 m long	■ Soil nail for pull-out test
• Working soil nail of 9 m long	⊙ Working soil nail of 7 m long

Figure 13 - Location of Test Nails in Phase II Site Trial

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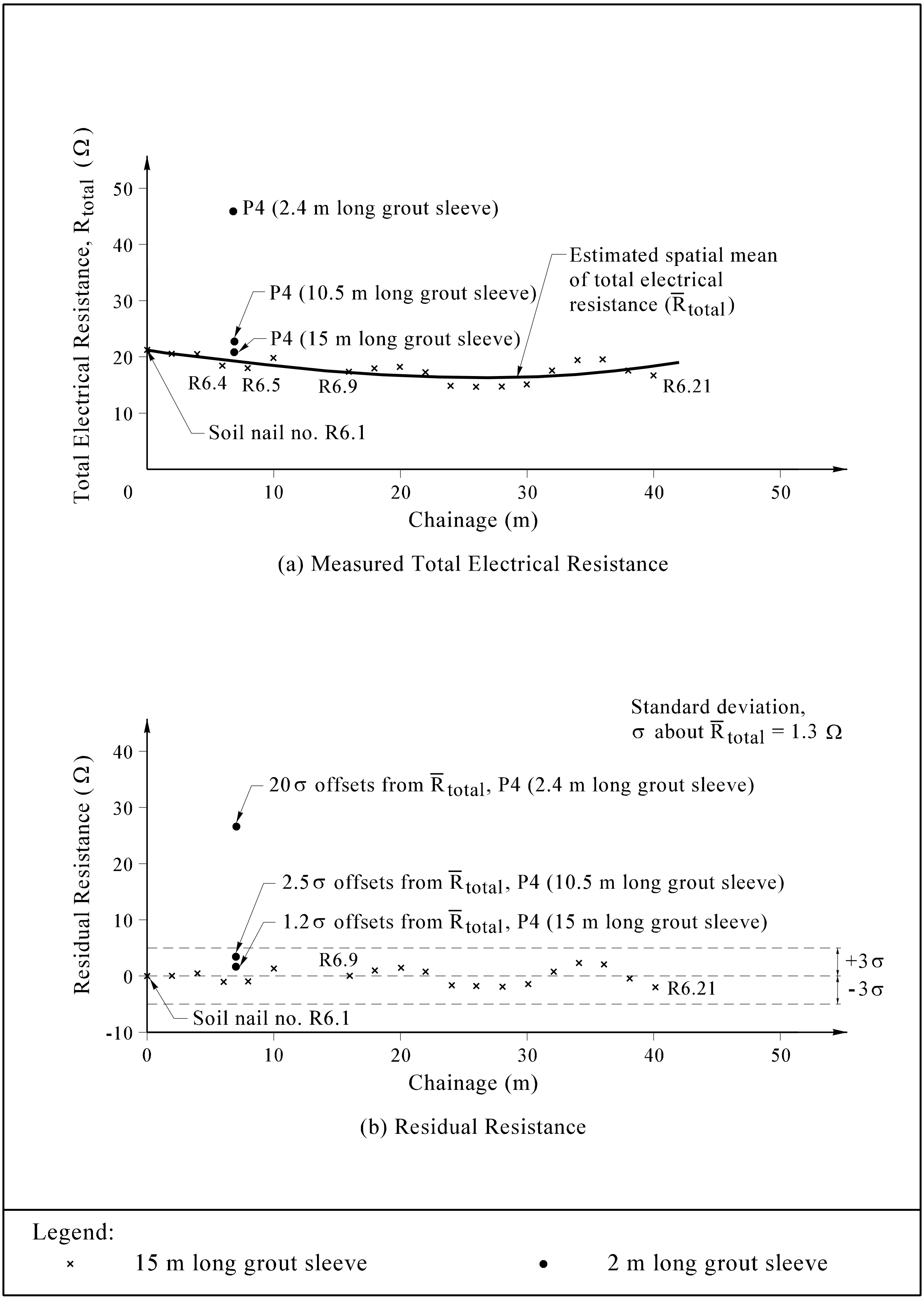

Figure 14 - Test Results of Soil Nails in Row 6 in Phase II Site Trial Using Electrical Resistance Method

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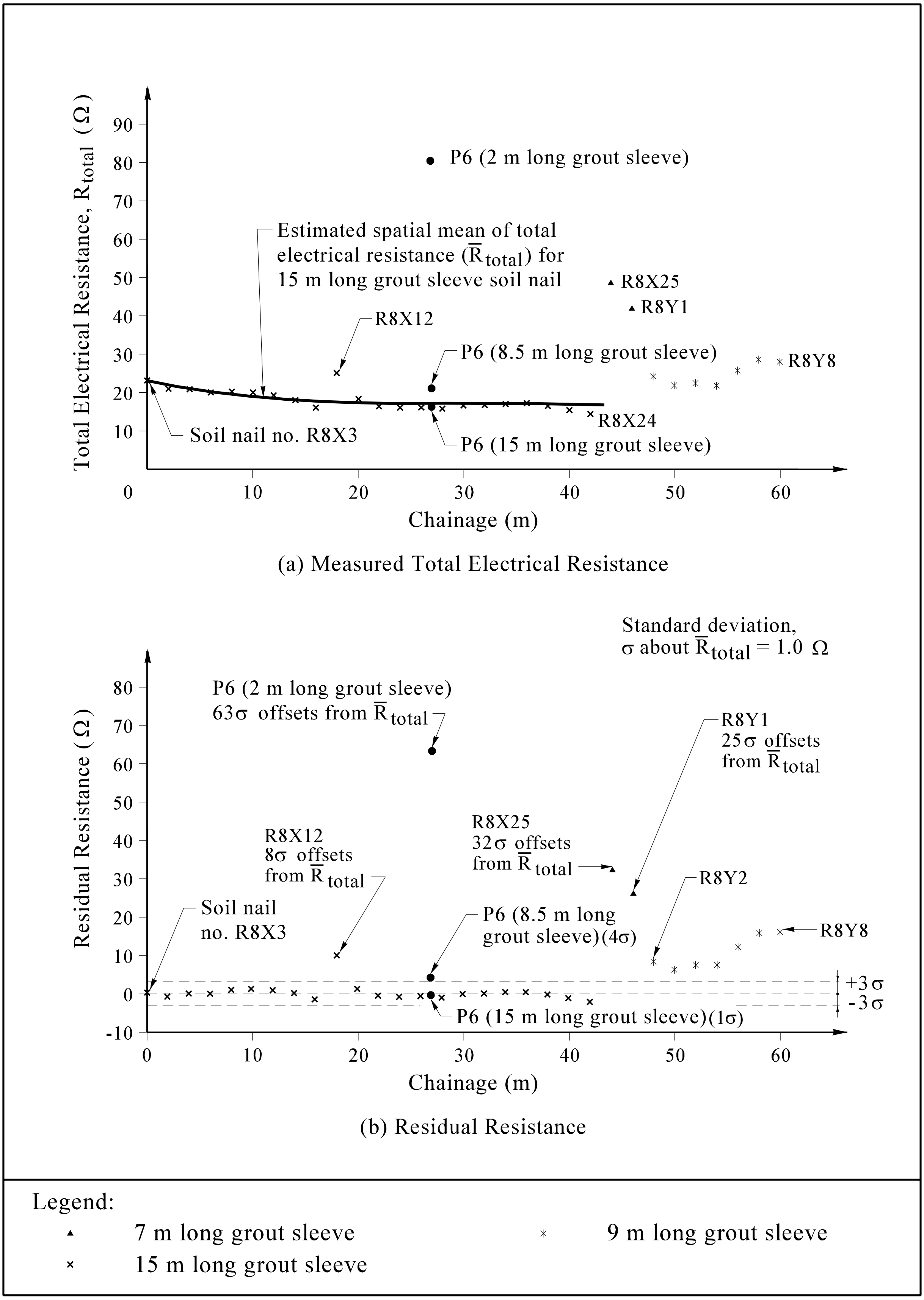

Figure 15 - Test Results of Soil Nails in Row 8 in Phase II Site Trial Using Electrical Resistance Method

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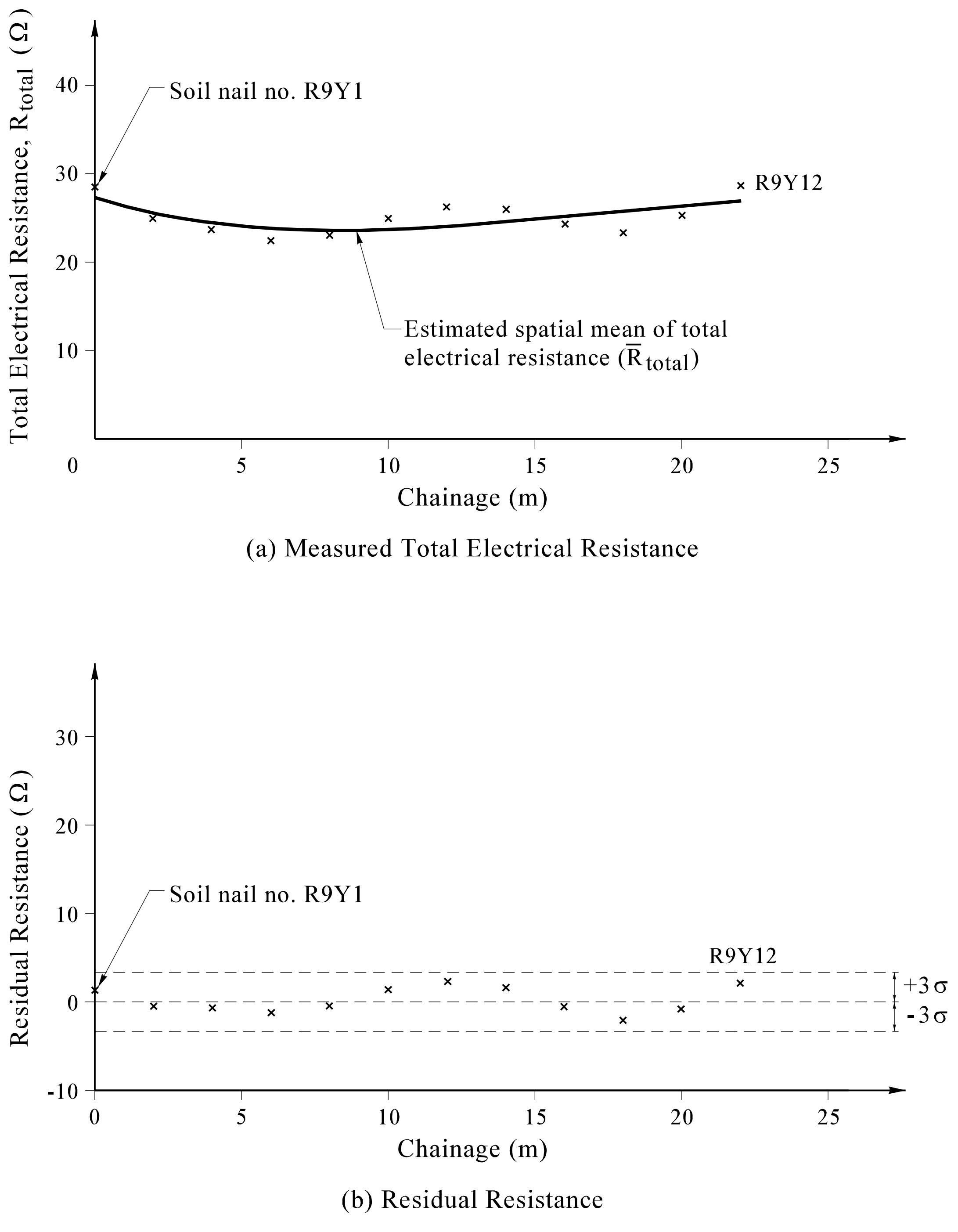

Legend:

× 9 m long grout sleeve

Figure 16 - Test Results of Soil Nails in Row 9 in Phase II Site Trial Using Electrical Resistance Method

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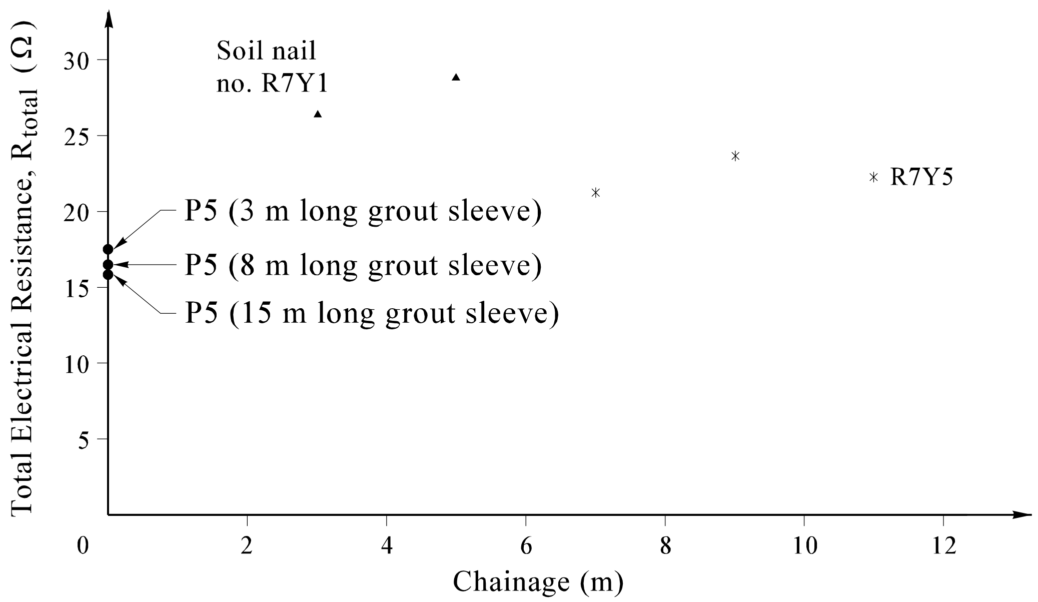

Legend:
▲ 7 m long grout sleeve
⁎ 9 m long grout sleeve

Figure 17 - Test Results of Soil Nails in Row 7 in Phase II Site Trial Using Electrical Resistance Method

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Plate 1 - Prefabricated Soil Nails

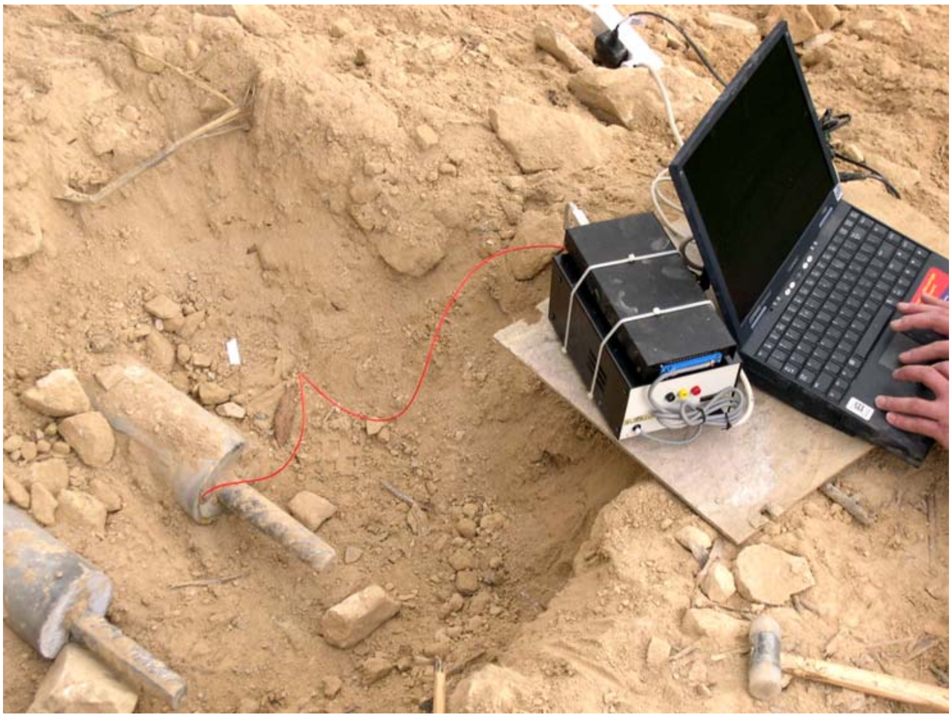

Plate 2 - Instrument Used in Sonic Echo Method

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Plate 3 - Instrument Used in Surface Wave Time Domain Reflectometry

Plate 4 - Instrument Used in the 3-pole AC Electrical Resistance Method

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Plate 5 - Measurement of Electrical Resistance at a Working Nail

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APPENDIX A

TESTING PROCEDURE OF THE ELECTRICAL RESISTANCE METHOD

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TESTING PROCEDURE OF THE ELECTRICAL RESISTANCE METHOD

(i) Install two stainless steel electrodes at linear distance from the test site. The spacing of the electrodes should be approximately 20 m to 50 m (see Figure 5 of this Report), and they should be installed to a depth of 0.5 m to 1 m below the ground level.

(ii) Connect the test nail and the electrodes by a standard AC three electrode earthing resistance monitoring equipment.

(iii) Close the electric current and potential measuring circuits. Take at least two measurements on each test nail to obtain a stable reading.

(iv) Repeat steps (i) to (iii) for all soil nails to be tested. It is preferable to take measurement along a row of soil nails.

Notes:
(1) The head of the steel soil nail to be tested shall be electrically accessible.
(2) Measurement should be taken upon completion of the curing process of the cement grout sleeve (normally three to seven days after grouting works).
(3) If the site is large, say more than 100 m long, it should be divided into sections for separate testing and examination.

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

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.

GEOGUIDES

Geoguide 1	Guide to Retaining Wall Design, 2nd Edition (1993), 258 p. (Reprinted, 2000).
Geoguide 2	Guide to Site Investigation (1987), 359 p. (Reprinted, 2000).
Geoguide 3	Guide to Rock and Soil Descriptions (1988), 186 p. (Reprinted, 2000).
Geoguide 4	Guide to Cavern Engineering (1992), 148 p. (Reprinted, 1998).
Geoguide 5	Guide to Slope Maintenance, 3rd Edition (2003), 132 p. (English Version).
岩土指南第五冊	斜坡維修指南，第三版(2003)，120頁(中文版)。
Geoguide 6	Guide to Reinforced Fill Structure and Slope Design (2002), 236 p.

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Geospec 1	Model Specification for Prestressed Ground Anchors, 2nd Edition (1989), 164 p. (Reprinted, 1997).
Geospec 2	Model Specification for Reinforced Fill Structures (1989), 135 p. (Reprinted, 1997).
Geospec 3	Model Specification for Soil Testing (2001), 340 p.

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GEO Publication No. 1/93	Review of Granular and Geotextile Filters (1993), 141 p.
GEO Publication No. 1/96	Pile Design and Construction (1996), 348 p. (Reprinted, 2003).
GEO Publication No. 1/2000	Technical Guidelines on Landscape Treatment and Bio-engineering for Man-made Slopes and Retaining Walls (2000), 146 p.

GEOLOGICAL PUBLICATIONS

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.

TECHNICAL GUIDANCE NOTES

TGN 1	Technical Guidance Documents

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