

NON-DESTRUCTIVE TESTS FOR DETERMINING THE LENGTHS OF INSTALLED STEEL SOIL NAILS

GEO REPORT No. 133

W.M. Cheung

**GEOTECHNICAL ENGINEERING OFFICE
CIVIL ENGINEERING DEPARTMENT
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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. A charge is made to cover the cost of printing.

The Geotechnical Engineering Office also publishes guidance documents as GEO Publications. These publications and the GEO Reports may be obtained from the Government's Information Services Department. Information on how to purchase these documents is given on the last page of this report.



R.K.S. Chan
Head, Geotechnical Engineering Office
May 2003

FOREWORD

This Report presents the results of a study on identifying and developing potential non-destructive methods for determining the lengths of drillholes and installed steel soil nails.

In this study, a review of international and national standards on design and construction of soil nails has been carried out. Field trials using the selected test methods and an assessment of their reliability and accuracy have been conducted. Recommendations are made for field application and further development.

This study was carried out by Mr WM Cheung of the Special Projects Division under the supervision of Mr YK Shiu and Mr Charles HC Chan. Much of the data collection and site supervision work was performed by the technical officers Mr WY Yeung (former GEO staff) and Mr KC Chan. Mr Philip WK Chung and Mr WP Chan of the Materials Division developed the Electro-magnetic Induction method. Valuable assistance in arranging field trials was provided by the staff of the Advisory Division, Design Division, Works Division and Water Supplies Department. A number of colleagues have provided useful comments on a draft version of this Report. All contributions are gratefully acknowledged.



WK Pun
Chief Geotechnical Engineer/Special Projects

ABSTRACT

Steel soil nails are used extensively for slope improvement works in Hong Kong. In order to enhance the quality control of the soil nail installation works, an in-house project has been conducted by the Geotechnical Engineering Office of Civil Engineering Department aiming at identifying and developing effective non-destructive means for determining the lengths of drillholes and installed steel soil nails.

The study has identified two techniques for determining the lengths of drillholes and five techniques for determining the lengths of installed steel soil nails. The former two techniques include methods of utilising a plastic tube and a rod, and the drilling process monitoring developed by the Hong Kong Jockey Club Research and Information Centre for Landslip Prevention and Land Development of the University of Hong Kong. The latter five techniques include the Sonic Echo method, the Mise-a-la-Masse method, Magnetometry, the Electro-magnetic Induction method and Time Domain Reflectometry. All these techniques have been investigated and tried out in the field. Merits and limitations of these methods are discussed in the Report.

Based on the study, Magnetometry and Time Domain Reflectometry have been identified as the most suitable methods for application in existing soil nailed slopes. For new soil nailed slopes, it is recommended to install plastic tubes or electric wires along with the steel nails and to allow the use of the Electro-magnetic Induction method or Time Domain Reflectometry respectively as a method for quality control testing. Further development work on the Electro-magnetic Induction method with a single pre-installed plastic tube and Time Domain Reflectometry without the need of an electric wire is also recommended.

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1. INTRODUCTION

Soil nailing has become one of the most common methods in slope improvement works. In order to enhance the quality control of the soil nail installation, a study has been conducted by the Geotechnical Engineering Office of Civil Engineering Department. It aims at identifying and developing effective non-destructive means for determining the lengths of drillholes and installed steel soil nails. Two techniques for determining the lengths of drillholes and five techniques for determining the lengths of steel soil nails have been identified, developed and studied. These techniques have been investigated in both the laboratory and 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; Department of Transport, 1994; Murray, 1993), France (French National Research Project, 1991) and Japan (Japan Highway Public Corporation, 1998). None of these documents contains guidelines on non-destructive means for determining the lengths of installed soil nails.

3. INVESTIGATION TECHNIQUES FOR DETERMINING THE LENGTHS OF DRILLHOLES

3.1 Plastic Tube and Rod

3.1.1 Principle

The principle of this technique is simple. During the course of soil nail installation, a small diameter (about 10 mm I.D.) plastic tube is fixed on the outer side of centralisers along the steel soil nail as illustrated in Figure 1. Both ends of the plastic tube are sealed by tape or sealant to prevent ingress of grout. The steel soil nail is then inserted into the drillhole (see Plate 1) and grouting is carried out as usual. The lengths of the plastic tube and the drillhole can be determined at any time by inserting a flexible plastic rod into the plastic tube (see Plate 2).

3.1.2 Site Trial

Trials were carried out at an in-house Landslip Preventive Measures (LPM) site in Tai Mei Tuk, Tai Po, and the results indicate that the method is practicable and successful. The technique has since been used in a number of LPM sites and is found satisfactory.

3.1.3 Merits and Limitations

This method is reliable and can be conducted rapidly. It does not require experienced personnel to carry out the measurement and interpret the results. The length of a drillhole can be determined at any time provided that the pre-installed plastic tube is not blocked or

buckled. However, the presence of a plastic tube introduces uncertain effect on the integrity of grout surrounding the nail bar. Particular attention is also required in choosing and fixing the plastic tubes in order to prevent them from kinking.

3.2 Drilling Process Monitoring

3.2.1 Principle

The Hong Kong Jockey Club Research and Information Centre for Landslip Prevention and Land Development of the University of Hong Kong has developed a prototype digital drilling process monitor (DPM) technique. The digital DPM can continuously measure and record the drilling process and parameters. These include the forward and backward movements, stoppage, forward and reverse rotations of the drilling rod and head, the dynamic pressures and loads that are applied to control and operate the drilling rod and head, and the length of a drillhole. Plates 3 and 4 show a percussive rotary drilling rig equipped with the DPM.

3.2.2 Site Trial

A trial has been carried out at an LPM site. Yue et al (2001) concluded from this site trial that the DPM could provide factual data on the drillhole lengths amongst other information.

3.2.3 Merits and Limitations

This is a quick and reliable method. However, the additional cost and time incurred may make it less attractive if only the lengths of drillholes amongst other information is of interest. The requirement for experienced personnel for interpreting the monitoring results and the fact that information on drillhole length can only be obtained during the drilling process add further limitations on this method.

4. INVESTIGATION TECHNIQUES FOR DETERMINING THE LENGTHS OF STEEL SOIL NAILS

4.1 Sonic Echo (Low-strain Integrity) Method

4.1.1 Principle

The principle of this method is based on that of the low-strain pile integrity test (Turner, 1994, 1995 and 1997). This method involves the examination of the generation, transmission and reception of an acoustic wave in a steel soil nail or in grout. The acoustic wave is commonly known as stress wave or shock wave. A stress wave is usually generated by striking the bar head with a light hand-held hammer (1 to 2 kg) (see Plate 5). The passage of the stress wave along a steel soil nail and the grout embedding the nail is affected by (i) the initial excitation force, (ii) the physical properties of the steel soil nail and grout, and (iii) the physical properties of the ground surrounding the nail. Due to significant change in physical properties at the nail end, a major wave reflection will occur at the nail end.

By analysing the reflected stress wave received from either the steel soil nail or the grout, the location of bar end can be detected. Figure 2 illustrates schematically the principle of this method. The governing equation of this method is:

$$L = \frac{V_s \cdot t}{2} \dots\dots\dots (1)$$

where L = the estimated length of the steel soil nail (m)
 V_s = the velocity of the stress wave propagating along the steel soil nail or grout as appropriate (ms^{-1})
 t = the time lapsed between the initial excitation and the arrival of the reflected stress wave (s)

The velocity of wave propagation in a soil nail can be determined either by calibrating with nails of known lengths or by deriving theoretically with the following equation:

$$V_s = \sqrt{\frac{E}{\rho}} \dots\dots\dots (2)$$

where E = the dynamic modulus of elasticity (Nm^{-2})
 ρ = the density of the material in which the stress wave propagates (kgm^{-3})

In steel soil nails, the velocity of acoustic wave propagation is about 5,000 m/s to 5,500 m/s, whereas in grout, the respective velocity is about 3,500 m/s to 4,000 m/s. Figure 3a illustrates the idealised waveform of a low-strain integrity test with the time elapsed between the initial excitation and the arrival of subsequent reflected stress waves.

In practice, wave energy will be dissipated as a result of damping effect. The waveform received may be damped to such a degree that the reflected wave from the nail end cannot reach the sensor with sufficient energy after a certain period of time as shown in Figure 3b. This is particularly the case when the soil nail is long.

4.1.2 Site Trial

Trials were carried out on 30 soil nails at 11 cut slopes. The typical test procedure of the trials is shown in Appendix A and the test results are summarised in Table 1. The tests on eight of the slopes could not always give a recognisable reflection for determining the lengths of the installed soil nails. At the remaining three slopes where soil nail lengths could be interpreted from the test results, the accuracy was quite variable. The error in the interpreted length was up to 11 m for a 16 m long steel soil nail. In summary, out of 30 soil nails tested, tests on 6 nails (20%) have no conclusive results, tests on 8 nails (27%) have errors equal to or greater than 10% and tests on 16 nails (53%) have errors less than 10%.

4.1.3 Merits and Limitations

Merits

- (a) This is a quick method and it takes only about half an hour to conduct a test.
- (b) The required instrument is readily available in the local market.
- (c) Provided that the steel nail head is accessible, this method can be applied.

Limitations

- (a) Attenuation (damping) may significantly affect the reliability and accuracy of this method. In general, attenuation of signal occurs as the wave travels along a soil nail. The amplitude of the reflected signal returning to the soil nail head could be much less than that of the excited signal. In some cases, the reflected signal may be so small that it cannot be differentiated from background noise. In general, for a given bar diameter, and grout and ground condition, the longer the steel soil nail, the greater the attenuation will be. Also, the stiffer the grout and ground surrounding the steel soil nail, the greater will be the attenuation.
- (b) Partial reflection is another factor that could reduce the reliability and accuracy of this method. Since this method is based on the transmission and reception of a stress wave in a steel soil nail or grout, the success and accuracy of the method depend on the degree of homogeneity of the physical properties of the steel soil nail, grout and the surrounding ground. The presence of a coupler or non-uniform grout section may generate partial wave reflections that would greatly increase the difficulty in identifying the true response reflected from the nail end. This phenomenon is illustrated in Figure 4.
- (c) Although the test can be carried out quickly, experienced personnel are required to interpret the results. This introduces human uncertainty in the interpreted results.
- (d) Concrete nail head has to be removed in order to provide access to the steel nail head for the test.
- (e) It is preferable to have calibration with nails of known lengths.

4.2 Mise-a-la-Masse Method (Equipotential)

4.2.1 Principle

Mise-a-la-Masse method is mainly used in mining exploration (ASCE, 1998). As suggested by its name “mise-a-la-masse (excitation of the mass)”, it describes the use of the conductive mass under investigation as one of the current electrodes. In this study, the conductive mass is the steel soil nail under investigation. This 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. Provided that 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. Figure 5 shows a theoretical equipotential surface of a homogeneous ground around a steel soil nail. Figure 6 shows the spatial distribution of electrical potential around a steel soil nail.

In practice, calibration against nails of known lengths is required for producing templates of potential distribution. Pairs of electrodes are implanted around a nail to be tested as shown in Figure 7 (see Plate 6 also). An electrical potential is applied by a battery with one end connected to the steel soil nail and the other end connected to a distant earthing point. The distribution of potential is determined through measuring the potential at each electrode. Calibration against nails of known lengths is necessary. The general set up of this method is shown in Plate 7.

4.2.2 Site Trial

Trials have been carried out at the LPM site in Tai Mei Tuk, Tai Po. The test procedure is given in Appendix A and the test results are summarised in Table 2. Although only two tests have been carried out, the measured nail lengths differ from the actual lengths by 8 m and 10 m. This indicates that the accuracy of this method is very low.

4.2.3 Merits and Limitations

Merits

- (a) Provided that the steel nail head is accessible, the method can be applied to all nailed slopes.

Limitations

- (a) 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, in particular moisture content, salt content, temperature, etc. It is a major, however, highly variable factor that affects the distribution of electrical potential around the steel soil nail, and hence the accuracy of the nail length estimation.
- (b) Similar to ground resistivity, extraneous electrical currents, either natural or artificial, affects the distribution of electrical potential around a steel soil nail, and hence the results of the test. An example of the causes of extraneous current is the corrosion of buried pipelines.
- (c) The testing process is very time-consuming and it takes about two to three hours to conduct a test. Furthermore, it requires experienced personnel to perform the test and interpret the test results.

- (d) Concrete nail head has to be removed in order to provide access to steel nail head.
- (e) Calibration with soil nails of known lengths are required.
- (f) The required instrument may not be readily available in the local market.

4.3 Magnetometry

4.3.1 Principle

The Earth possesses a magnetic field caused by sources in its core. Most materials exhibit an induced local magnetic field (induced magnetization) when they are subject to a strong field such as the Earth's magnetic field. In other words, materials behave as small magnets under a strong magnetic field. The induced local field intensity depends on the intensity of the strong field and the ability of the materials to enhance the local field. This enhancement ability is measured by a property called volume magnetic susceptibility. It is a measure of how susceptible a material is to becoming magnetised. The volume magnetic susceptibility is defined as:

$$\kappa = \frac{I}{F} \dots\dots\dots (3)$$

where κ = the volume magnetic susceptibility (m^{-3})
 F = the field intensity in tesla (T)
 I = the induced local magnetisation per unit volume (Tm^{-3})

For most soil and rock types, the volume magnetic susceptibility is in the order of 10^{-3} to 10^{-5} , whereas for ferrous materials such as steel, it is in the order of 10^2 to 10^3 (ASCE, 1998). Because of their high volume magnetic susceptibility, ferrous materials could cause substantial local distortion of the Earth's magnetic field. A steel soil nail possesses a high magnetic retentivity, which is manifested as a strong permanent magnetic polarisation. The steel soil nail is polarised with a magnetic field diverges radially at one end and converges radially at the other end. Two bars connected together with a coupler would introduce complex magnetic dipole patterns at the location of the connection. Thus, by measuring the fluctuation of Earth's magnetic field in the vicinity of a soil nail, the presence of a steel bar can be identified. 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 the insertion of an instrument called magnetometer (see Plate 8). This instrument can measure the Earth's field and hence the distortion caused by the presence of the steel soil nail. Figure 8 shows a theoretical profile of magnetic field in two perpendicular directions to a steel soil nail, namely M_x , M_y . In practice, a magnetometer would measure the Earth's field in three orthogonal directions, namely M_x , M_y (perpendicular to the steel bar) and M_z (along the steel bar). By analysing the fluctuation of these magnetic vectors, the positions of the couplers and the bar ends can be identified.

4.3.2 Site Trial

Trials using this method have been carried out at a Water Supplies Department's

(WSD) site in Yau Tong and an LPM site at Sheung Lok Street, Homantin. The test procedures of this method are given in Appendix A and the test results are summarised in Table 3. Out of the seven tests on nails, six have errors of the interpreted lengths less than one metre (actual nail lengths vary from 6 m to 16 m). The remaining test has an error of about 1.3 m for a 6 m long nail. This indicates that the reliability and accuracy of this method are quite high. Moreover, the presence of couplers and their locations can be identified and located accurately except for one test nail.

4.3.3 Merits and Limitations

Merits

- (a) This is a quick method if Procedure A (without attaching a magnet to the head of a test nail, see Appendix A) is followed and the test takes less than half an hour to conduct.
- (b) There is no need to gain access to the head of a steel soil nail and hence the concrete nail head can be retained. In this connection, this method can be applied to all nailed slopes.
- (c) It is relatively more reliable and accurate if compared with other methods that have been investigated in this study. The accuracy in measuring the length of a steel soil nail is in the order of ± 1 m. Furthermore, this method is capable of detecting the locations of couplers.

Limitations

- (a) Additional cost is required for drilling the extra hole for the test. If the number of nails to be tested is large, the method may become economically less attractive. Although one drillhole (if Procedure B with a magnet attached to the head of a test nail is followed, see Appendix A) can serve several soil nails, the time required will be much longer. It takes about two to three hours to conduct a test.
- (b) The presence of overhead power lines, nearby radio broadcasting stations, etc may cause interference to the measurement near slope surface (about 2 m deep).
- (c) Experienced personnel are required to conduct the test and interpret test results.

4.4 Electro-magnetic Induction Method

4.4.1 Principle

This method was developed by the staff of the Public Works Central Laboratory. The principle is based on electro-magnetic induction. Electro-magnetic induction is the influence by which an electric current produces magnetic polarity in certain bodies near or around which it passes.

As illustrated in Figure 9, the device consists of an oscilloscope, a transformer and a

pair of probes. The probes are simply made of steel solenoids wrapped with copper wire for about 3,000 turns (see Plate 9), and they are connected with small plastic rods with markings of length. A prerequisite of this method is that a pair of small diameter plastic tubes (about 10 mm I.D.) have to be pre-installed along and at the opposite sides of the steel soil nail to be tested. These plastic tubes shall be extended beyond the end of the bar by at least 50 mm. During testing, the probes are inserted simultaneously, one into each of the pre-installed plastic tubes, and a voltage is applied to the emitter probe (see Plate 10). As illustrated in Figure 10, whenever the probes pass beyond the end of a steel soil nail (i.e. from the presence to the absence of a steel reinforcement between the probes), there is a noticeable increase in the voltage induced in the receiver probe. Thus, by studying the changes in the profile of the voltage induced in the receiver probe, the end of a steel soil nail can be detected.

4.4.2 Site Trial

Trials using this method have been carried out at a WSD's site in Yau Tong and an LPM site at Ching Cheung Road. The test procedure is shown in Appendix A and the test results are summarised in Table 4. The test results of all the eleven nails of lengths varying from 12 m to 20 m indicate that the method is reliable and has the highest accuracy (in the order of ± 0.1 m) amongst the five methods in this study. Trials have also been conducted to grout up the plastic tubes after the test. The results show that this is feasible if the far ends of the two tubes are connected together by a U-shaped tube.

4.4.3 Merits and Limitations

Merits

- (a) This is a quick method. It takes less than half an hour to conduct a test. Since no post-measurement analysis of the test data is required, the length of a steel soil nail can be determined during the test.
- (b) This method is reliable and has the highest degree of accuracy amongst the five methods that have been investigated in this study. The accuracy in determining the length of a steel soil nail is in the order of ± 0.1 m.
- (c) Experienced personnel for interpretation of test results are not required.
- (d) The required instrument components are readily available in the market.

Limitations

- (a) This method requires pre-installation of two plastic tubes for insertion of the probes. The effect of the presence of these plastic tubes on the integrity of soil nail is uncertain. Moreover, particular attention is required in choosing and fixing these plastic tubes to avoid possible tube kinking and blocking during the grouting operation.

- (b) Because of the requirement of pre-installed plastic tubes, this method cannot be applied to determine those installed nails without any provision of such tubes.

4.5 Time Domain Reflectometry (TDR)

4.5.1 Principle

Time Domain Reflectometry (TDR) was first developed in 1950s to detect faults (break or damage) in transmission cables (O'Connor & Dowding, 1999). TDR works on the same principle as radar and is a method of measuring the propagation time of high-frequency electrical signals in a pair of parallel cables (coaxial cable). When an electrical pulse is sent along a transmission line, a reflection will be caused by any discontinuity in the cable. Echoes will be observed in the oscilloscope. From the characteristics of the echoes (i.e. the transmission time, magnitude and polarity of the reflection), the spatial location and the nature of the discontinuity can be determined.

As illustrated in Figure 11, the configuration of a soil nail is analogous with a coaxial cable if an electric wire is pre-installed along a steel soil nail during soil nailing works (see Plate 11 also). The twin-conductor configuration (steel bar and electric wire) acts as a coaxial cable in a dielectric material (grout). The distributed parameter equivalent circuit of this transmission line is shown in the same Figure. It can be shown from the transmission line theory that the propagation velocity of an electromagnetic wave, V_p , travelling along a coaxial cable is given by:

$$V_p = \frac{1}{\sqrt{LC}} \dots\dots\dots(4)$$

where L = the cable inductance in unit of henries per metre
C = the capacitance in unit of farads per metre

This propagation velocity is related to the material properties by the following expression (Topp et al, 1980):

$$V_p = \frac{V_c}{\sqrt{\epsilon}} \dots\dots\dots(5)$$

where V_c = the speed of light in vacuum (3×10^8 m/s)
 ϵ = a dimensionless property called dielectric constant which measures how a material reacts under a steady-state electric field (for air $\epsilon \approx 1$, for grout $\epsilon \approx 10$ and for water $\epsilon \approx 80$)

Although the propagation velocity is not very sensitive to the variation of dielectric constant of grout (doubling the dielectric constant results in only a 30% reduction of propagation velocity), anomaly in the grout will cause ripples in the response signal. It would be preferable to have calibration of propagation velocity against nails of known lengths. As such, the propagation velocity derived from Equation (5) can serve as a reference to gauge the order of magnitude of the site-specific calibrated velocity. In this regard, the accuracy of the test method will be improved.

Figure 12 shows the set up of the TDR system with no electrical connection between the bar end and the electric wire. The theoretical responses from the steel soil nail of length L excited by a short pulse and a long pulse respectively are also shown in the same Figure. The time required for the pulses and their echoes to travel a distance of $2L$ is $(t_1 - t_0)$. Thus, the length of the steel soil nail is:

$$L = \frac{V_p \cdot (t_1 - t_0)}{2} \dots\dots\dots (6)$$

where t_0 = time of pulse excitation
 t_1 = time of arrival of response

Similar result can be obtained if the electric wire is connected to the nail end as shown in Figure 13. The only difference in the responses between this case and the case of no connection is in the polarity of the echoes. The connection detail between the pulse emitter and the test nail bar, and between the receiver and the pre-installed electric wire is shown in Plate 12. Plate 13 illustrates the set up of the TDR instrument.

If the electric wire is not provided, the above principle becomes inapplicable. To address this problem, the TDR instrument has been modified such that a so-called image electromagnetic wave is excited on the surface of the nail bar. As such, the steel soil nail can be modelled as a Goubau line (i.e. dielectric material coated on a single conductor line). This permits the reflected signal (i.e. the echo) to be measured with just one conductor. In practice, the reflected signal is not as strong as that obtained from a steel soil nail with the presence of an electric wire. As illustrated in Figure 14, the fuzziness of the reflected signal could introduce an error in the interpreted length of up to ± 1 m for a 6 m long steel soil nail. Further improvement work on this technology is being carried out.

4.5.2 Site Trial

Trials on using the method have been carried out at an LPM site at Sheung Lok Street, Homantin. The test procedure is given in Appendix A and the test results are summarised in Table 5. Results of the four tests with provision of an electric wire indicate that the errors of length determination vary from 0.1 m to 0.2 m for nail length of 6 m. Whereas the remaining fifteen tests without provision of an electric wire indicate that the errors of length determinations vary from 0.1 m to 0.7 m for nail lengths of 6 m to 12 m. The accuracy of this method could reach ± 1 m if the echo can be identified. However, as aforementioned, the echo from a nail without an electric wire is not as strong as that from one with an electric wire. Sometimes, it may even be difficult to identify the correct echo. As such, the reliability of the test method without an electric wire is lower than that with an electric wire.

4.5.3 Merits and Limitations

Merits

- (a) It is a quick method and it takes about half an hour to conduct a test.

- (b) This method is relatively reliable and accurate, especially when electric wires are pre-installed in the nails. The accuracy could reach about ± 1 m.

Limitations

- (a) Only limited number of the required instrument may be available in the local market.
- (b) Experienced personnel are required to perform the test and interpret the test results, especially if electric wires are not pre-installed with the nails.
- (c) Concrete nail head has to be removed in order to provide access to steel nail head.
- (d) It is preferable to have calibration, particularly for the test without pre-installed electric wire, with nails of known lengths before conducting the test, otherwise the accuracy of ± 1 m may not be achieved.

5. DISCUSSION

The merits and limitations of the five non-destructive methods for determining the lengths of installed steel soil nails have been discussed and they are summarised in Table 6. It is evident that the Sonic Echo and the Mise-a-la-Masse methods have the lowest reliability and accuracy among the five methods. These two methods should not be used until their reliability and accuracy are improved. The Electro-magnetic Induction method is the most accurate among the five methods. However, the need to pre-install plastic tubes and the uncertain effects of the tubes on the integrity of soil nails may make the method less attractive at this stage. Nevertheless, it has been found feasible to grout up the plastic tubes after the test. Magnetometry is an accurate and the most reliable method. During the site trials, Eastman-Whipstock camera has been used to determine the alignments of three randomly selected drillholes of lengths 16 m, 16 m and 18 m respectively. It is found that the actual alignments of these drillholes deviated from the specified profile by not more than 2° . The Magnetometry technique is able to cope with this deviation without loss of reliability and accuracy. However, if the deviation exceeds that can be tolerated, one can still use Procedure B (with a magnet attached to the test nail head) to retain the reliability and accuracy of this method. Magnetometry is particularly suitable for use, in forensic type studies, to determine lengths of existing soil nails. Additional cost for drilling the extra holes may render the method uneconomical if a large number of the nails are to be tested by this method. However, the cost of contract compliance testing can be substantially reduced if the method is used in conjunction with other more economical testing methods. Time Domain Reflectometry (TDR) is the most suitable method for use in soil nailed slopes with a pre-installed electric wire. Although the reliability and accuracy of this method will be reduced if no electric wire is pre-installed, this method can still be used as a quick testing method for supplementing other more accurate methods such as Magnetometry.

Since the non-destructive methods are capable of determining the lengths of installed steel soil nails, the plastic tube and rod method that can only be used for determining the lengths of drillholes becomes unnecessary.

Apart from non-destructive tests for determining the lengths of installed soil nails, information on destructive tests has also been collected from file records. Exhumation of steel soil nails were carried out before by means of stitch drilling (see Plate 14) and over-coring (see Plates 15 & 16). It is difficult to control the alignment of drilling and coring with respect to that of the installed soil nails unless the lengths of installed soil nails are short, say less than 10 m. This imposes limitations on using this method for long soil nails.

6. CONCLUSIONS AND RECOMMENDATIONS

From the trials of using the various methods to determine the lengths of steel soil nails, it is found that Magnetometry, the Electro-magnetic Induction method and Time Domain Reflectometry (TDR) are both reliable and sufficiently accurate for practical purposes. These methods have the greatest potential for field application. Among these three methods, the Electro-magnetic Induction method has the highest accuracy. However, further investigation would be useful to alleviate the concern over the effects of the plastic tubes that have to be installed on the nail integrity, before introducing it for routine use.

For investigation of a small number of steel soil nails in existing soil nailed slopes, Magnetometry could be used. However, if a large number of soil nails are to be tested, Magnetometry could be used in conjunction with TDR in view of the high cost associated with drilling extra holes for the test.

For works contract compliance testing of new soil nails, it is recommended to install an electric wire along the steel soil nail and use TDR for checking the length of steel soil nail. Alternatively, two small diameter plastic tubes can be installed along the steel soil nail and the Electro-magnetic Induction method is used to conduct the same checking. For the TDR technique, the electric wire should be isolated electrically from the steel soil nail to prevent corrosion due to dissimilar metals. In order to get familiar with the test methods with regard to their reliability and accuracy, it is recommended that more extensive site trials using the techniques of TDR and Electro-magnetic Induction be carried out before they are to be adopted for routine use.

In the long run, further development work on the Electro-magnetic Induction method with a single pre-installed plastic tube and the TDR technique without a pre-installed electric wire for determining the lengths of steel soil nails should be carried out.

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Table 1 - Test Results of Using the Sonic Echo Method to Determine Lengths of Soil Nails at 11 Cut Slopes (Sheet 1 of 2)

Contract No.	Feature No.	Soil Nail No.	As-built Soil Nail Bar Length (m)	Diameter of Soil Nail Bar (mm)	Estimated Nail Bar Length (m) ¹	Estimated Nail Bar Length (m) ²
GE/98/09	11SE-C/C17	SN126	12.0	32	11.7	-
		PN9	8.0 (2 m grout)	32	5.0	-
	11SW-D/C620	SN14	12.0 (6 m void in grout pipe)	32	No recognisable reflection	11.7
		SN18	12.0 (6 m void in grout pipe)	32	12.2	12.8
	11SW-A/CR28 & C29	SN56	16.0 (4 + 4 + 4 + 4) ³	40	16.4	16.5
		SN128	12.0 (4 + 4 + 4)	40	No recognisable reflection	12.2
		SN149	8.0 (4 + 4)	40	No recognisable reflection	No recognisable reflection
	11SW-D/C106	SN385	15.0 (6 + 6 + 3)	32	14.8	No recognisable reflection
		SN408	15.0 (6 + 6 + 3)	32	No recognisable reflection	14.5
		SN426	15.0 (6 + 6 + 3)	32	No recognisable reflection	14.6
	15NE-A/C42	AN45	8.0 (4 + 4)	32	No recognisable reflection	No recognisable reflection
		SN75	8.0 (4 + 4)	32	No recognisable reflection	7.7
		SN141	8.0 (4 + 4)	32	No recognisable reflection	8.2
	11SE-C/C59	A-1	8.0	25	8.7	9.0
		AS-1	8.0	25	No recognisable reflection	N/A
		ASN-14	14.0	25	No recognisable reflection	N/A

Table 1 - Test Results of Using the Sonic Echo Method to Determine Lengths of Soil Nails at 11 Cut Slopes (Sheet 2 of 2)

Contract No.	Feature No.	Soil Nail No.	As-built Soil Nail Bar Length (m)	Diameter of Soil Nail Bar (mm)	Estimated Nail Bar Length (m) ¹	Estimated Nail Bar Length (m) ²
GE/99/18	11SW-C/C68	R5/1	6.0	25	3.4	No recognisable reflection
		R5/8	6.0	25	No recognisable reflection	N/A
	11SE-D/C88	Row1-7	6.0	25	2.1	No recognisable reflection
		Row1-9	6.0	25	No recognisable reflection	No recognisable reflection
	11SE-D/C98	Row2-6	6.0	25	5.0	N/A
		Row6-3	6.0	25	4.2	N/A
GE/2000/14	11NW-A/C54	D81	16.0 (4 + 4 + 4 + 4)	32	9.9	N/A
		D86	16.0 (4 + 4 + 4 + 4)	32	16.0	N/A
		D87	16.0 (4 + 4 + 4 + 4)	32	16.8	N/A
		D90	16.0 (6 + 4 + 6)	32	4.8	N/A
		F65	12.0 (6 + 6)	32	11.9	N/A
		F69	12.0 (6 + 6)	32	11.6	N/A
		F71	12.0 (6 + 6)	32	11.9	N/A
		F72	12.0 (6 + 6)	32	11.9	N/A
Notes: (1) Sensor (accelerometer) mounted on steel bar. (2) Sensor (accelerometer) mounted on grout. (3) (4 + 4 + 4 + 4) means four segments of nail bar of 4 m length each.						

Table 2 - Test Results of Using the Mise-a-la-Masse Method

Feature No.	Soil Nail No.	Diameter of Nail Bar (mm)	As-built Nail Bar Length (m)	Estimated Nail Bar Length (m)
3SE-D/CR 121	A6	32	10	2 - 2.5
3SE-D/CR 123	A1	32	12	1 - 2

Table 3 - Test Results of Using Magnetometry

Site/Feature No.	Soil Nail No.	Procedure Adopted	Diameter of Nail Bar (mm)	Separation between Nail Bar and Drillhole (m)	As-built Nail Bar Length (m)	Estimated Nail Bar Length (m)
Sheung Lok Street, Homantin/ 11NW-D/C222	A47	A	25	0.38	12 (6 + 6)	11.9 (5.9 + 6)
	C29	A	25	0.39	8 (8)	7.1 (5 + 2.1)
	C31	A	25	0.33	12 (6 + 6)	11.2 (5.2 + 6)
	C32	A	25	0.42	10 (4 + 6)	9.7 (4.7 + 5)
	D26	A	25	0.28	6 (6)	5.6 (5.6)
	D27	A	25	0.32	6 (6)	4.7 (4.7)
Yau Tong WSD Fresh Water Reservoir	4	B	40	1.15	16 (6 + 4 + 6)	16 (6 + 4 + 6)
Note: Please refer to Appendix A for Procedures A and B.						

Table 4 - Test Results of Using the Magnetic-Induction Method

Site/Feature No.	Soil Nail No.	Diameter of Nail Bar (mm)	As-built Nail Bar Length (m)	Estimated Nail Bar Length (m)
Ching Cheung Road/ 11NW-A/C54	H41	32	12	12.0
	H45	32	12	12.0
	H85	32	20	20.0
	H88	32	20	20.1
	H91	32	20	19.9
	AB52	32	20	19.9
	AB53	32	20	20.0
	AB54	32	20	20.1
Yau Tong WSD Fresh Water Reservoir/Slope No. 3	1	40	16	16.0
	2	40	16	16.0
	4	40	16	16.0

Table 5 - Test Results of Using Time Domain Reflectometry

Site/Feature No.	Soil Nail No.	Presence of Cable	Diameter of Nail Bar (mm)	As-built Nail Bar Length (m)	Estimated Nail Bar Length (m)
Sheung Lok Street, Homantin/ 11NW-D/C222	A46	N	25	12	12.1
	A47	N	25	12	12.7
	C17	Y (open circuit)	25	6	6.2
	C18	Y (open circuit)	25	6	5.9
	C20	Y (close circuit)	25	6	6.1
	C21	Y (close circuit)	25	6	5.9
	C28	N	25	8	8.2
	C29	N	25	8	7.9
	C32	N	25	10	9.7
	C33	N	25	10	10.0
	C34	N	25	6	6.0
	C35	N	25	6	6.3
	C36	N	25	6	6.4
	C37	N	25	6	6.5
	D17	N	25	5	5.1
	D25	N	25	6	6.3
	D26	N	25	6	6.1
	D27	N	25	6	6.1
	D28	N	25	6	6.2

Table 6 - Merits and Limitations of Different Testing Methods

	Sonic Echo Method	Mise-a-la-Masse Method	Magnetometry	Electro-magnetic Induction	Time Domain Reflectometry	
					With Electric Wire	Without Electric Wire
Merits	<ul style="list-style-type: none"> - quick - instrument readily available in the local market - feasible for all soil nailed slopes 	<ul style="list-style-type: none"> - feasible for all soil nailed slope 	<ul style="list-style-type: none"> - quick - both the locations of couplers and bar end can be identified - concrete nail head can be retained - feasible for all soil nailed slope 	<ul style="list-style-type: none"> - quick - experienced personnel for result interpretation is not required - instrument readily available in the local market 	<ul style="list-style-type: none"> - quick 	<ul style="list-style-type: none"> - quick - feasible for all soil nailed slopes
Limitations	<ul style="list-style-type: none"> - reliability subject to attenuation and partial reflection - require experienced personnel to interpret test results - concrete nail head has to be removed - preferable to have calibration with nails of known lengths 	<ul style="list-style-type: none"> - time consuming - reliability subject to high uncertainties of ground resistivity and extraneous electrical currents - require experienced personnel to interpret test results - concrete nail head has to be removed - instrument may not readily available in the local market - require calibration with nails of known lengths 	<ul style="list-style-type: none"> - additional cost is required for drilling holes - results near slope surface subject to interference by overhead power lines, radio broadcasting stations, etc. - instrument may not readily available in the local market - require experienced personnel to interpret test results 	<ul style="list-style-type: none"> - pre-installation of plastic tubes is required - effect of plastic tubes on the integrity of soil nail is unknown if they are left open - not feasible for soil nailed slopes without provision of plastic tubes 	<ul style="list-style-type: none"> - pre-installation of electric wire is required - not feasible for soil nailed slopes without provision of electric wire - require experienced personnel to interpret test results - concrete nail head has to be removed - preferable to have calibration with nails of known lengths 	<ul style="list-style-type: none"> - require experienced personnel to interpret test results - concrete nail head has to be removed - preferable to have calibration with nails of known lengths
Accuracy	Low	Very Low	High (± 1 m)	Very High (± 0.1 m)	High ($< \pm 1$ m)	High (± 1 m)
Reliability	Moderate	Low	High	High	High	Moderate

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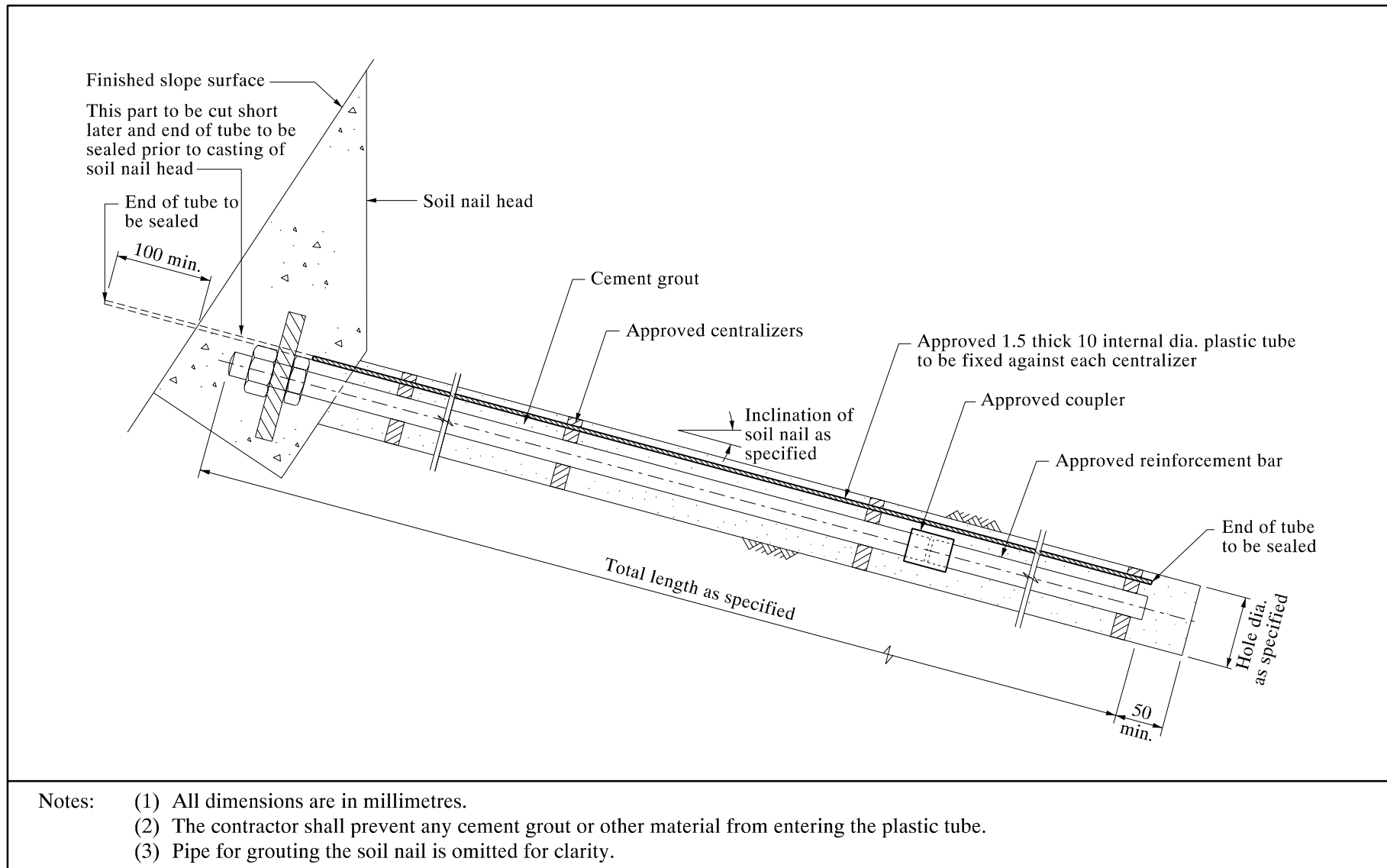


Figure 1 - Details of Provision of Plastic Tube for Checking of Drillhole Depth

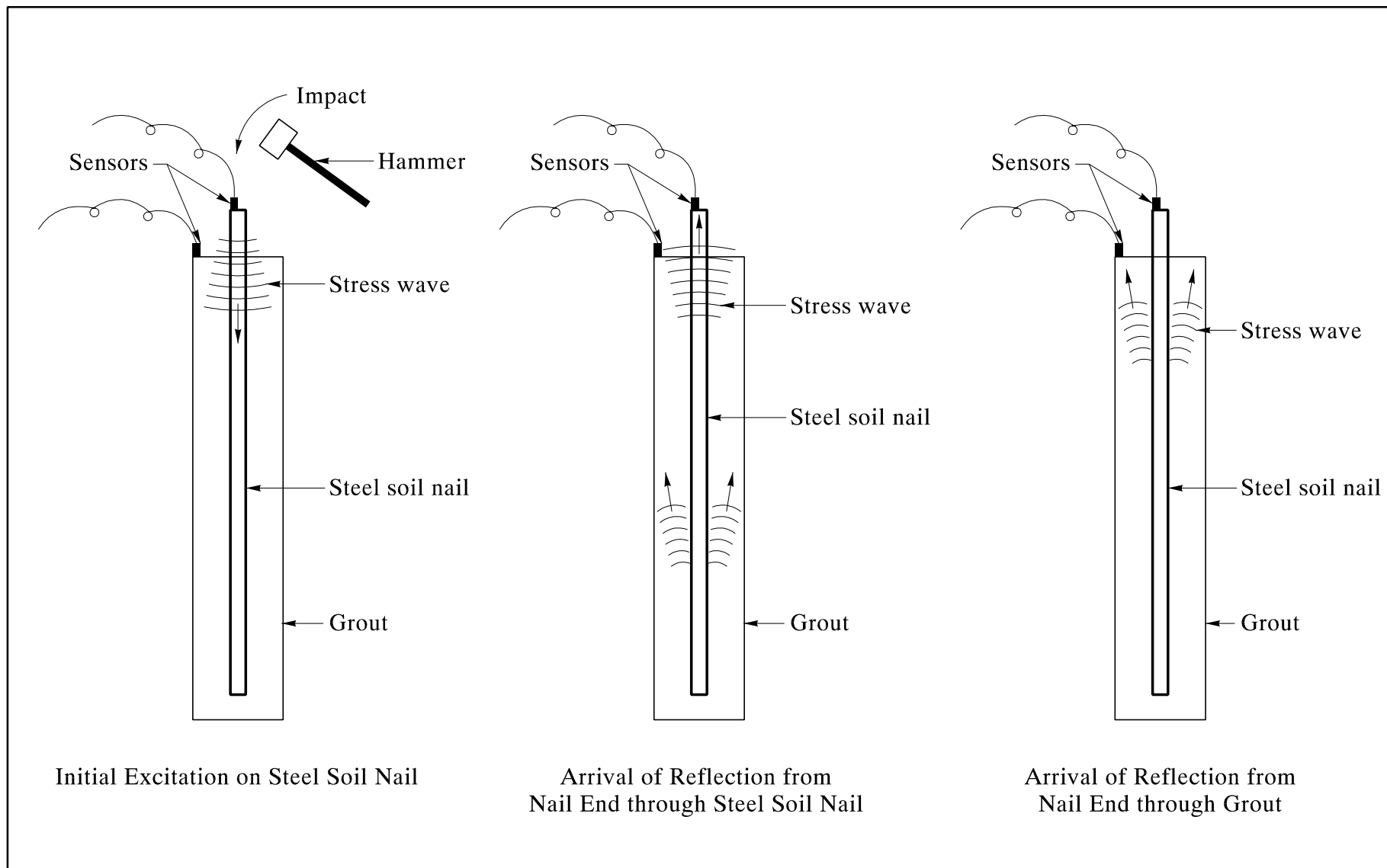
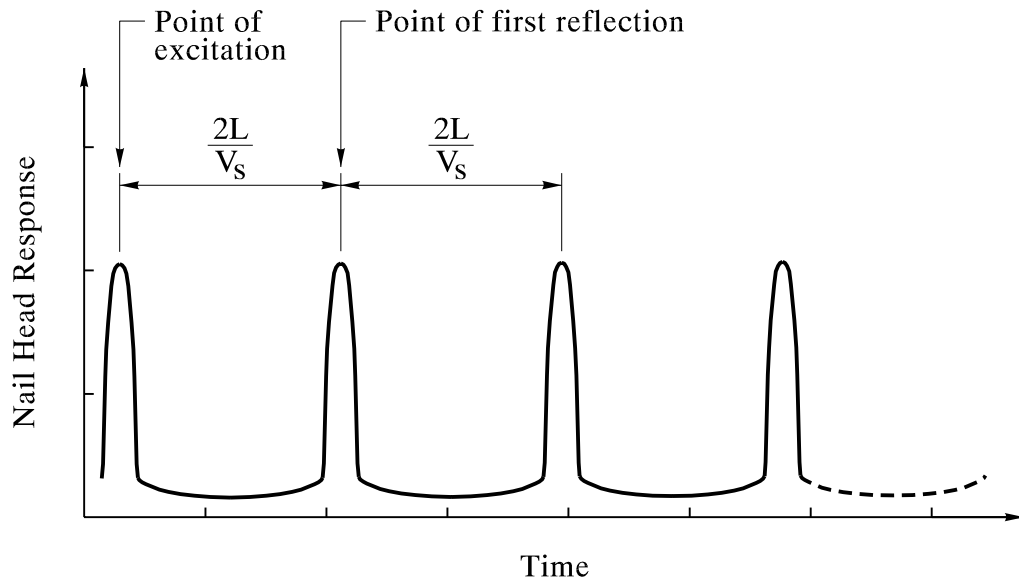
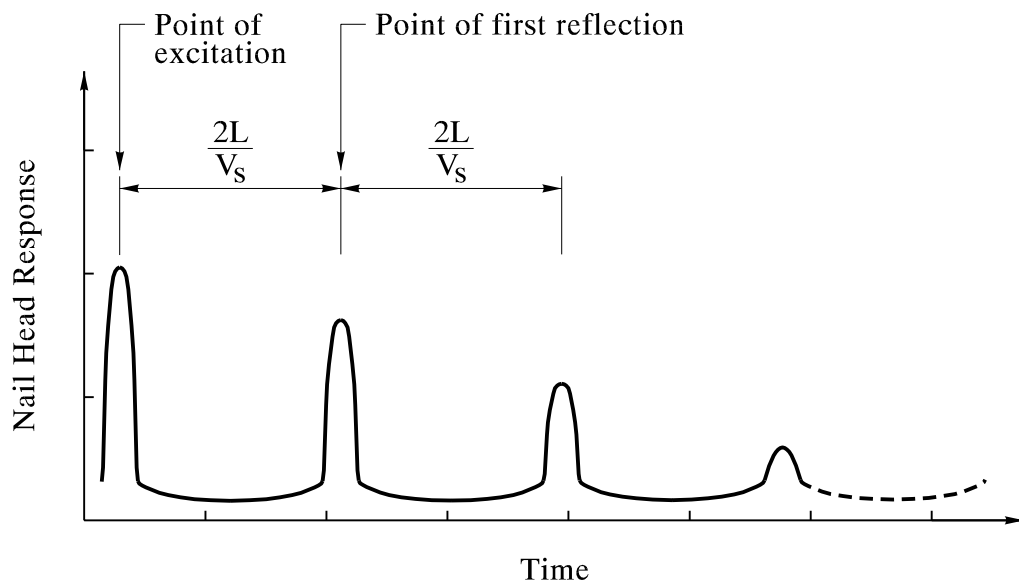


Figure 2 - Principle of the Sonic Echo Test



(a) Idealised Response Waveform of the Sonic Echo Test



(b) Idealised Damping Response Waveform of the Sonic Echo Test

Figure 3 - Idealised Response Waveform of the Sonic Echo Test

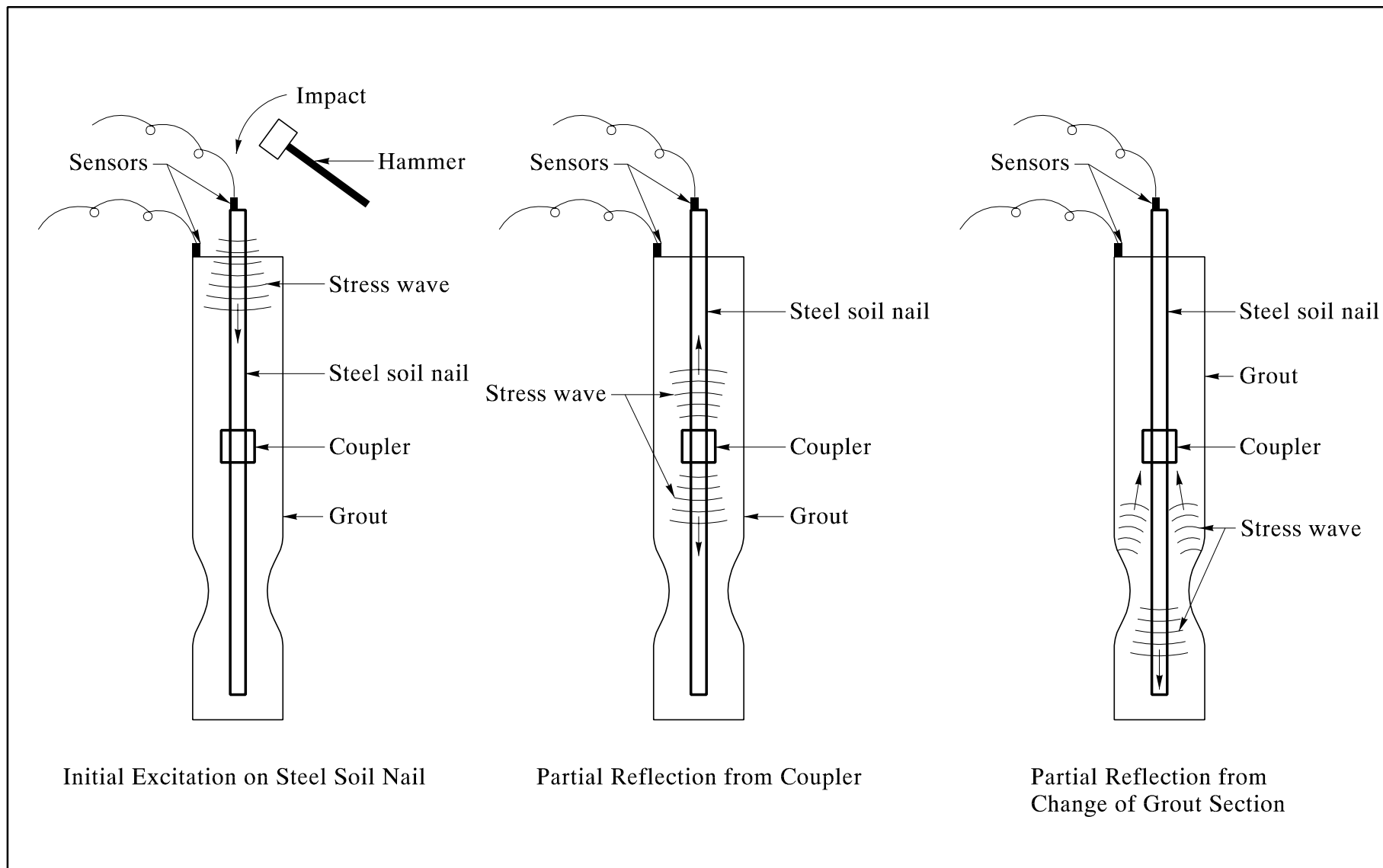


Figure 4 - Partial Reflection a Soil Nail

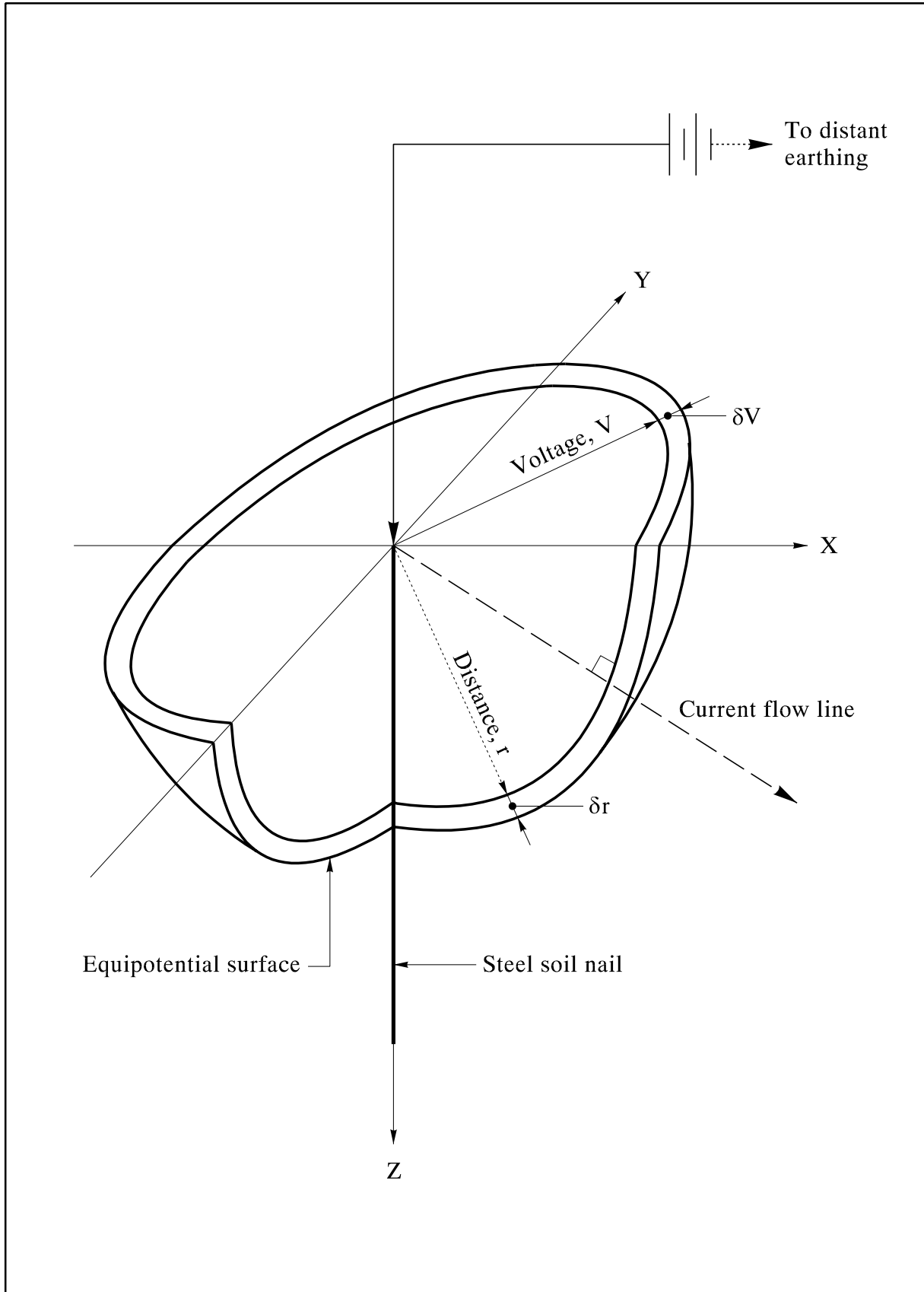


Figure 5 - Equipotentials and Current Flow Line Around a Steel Soil Nail on a Homogeneous Half-space

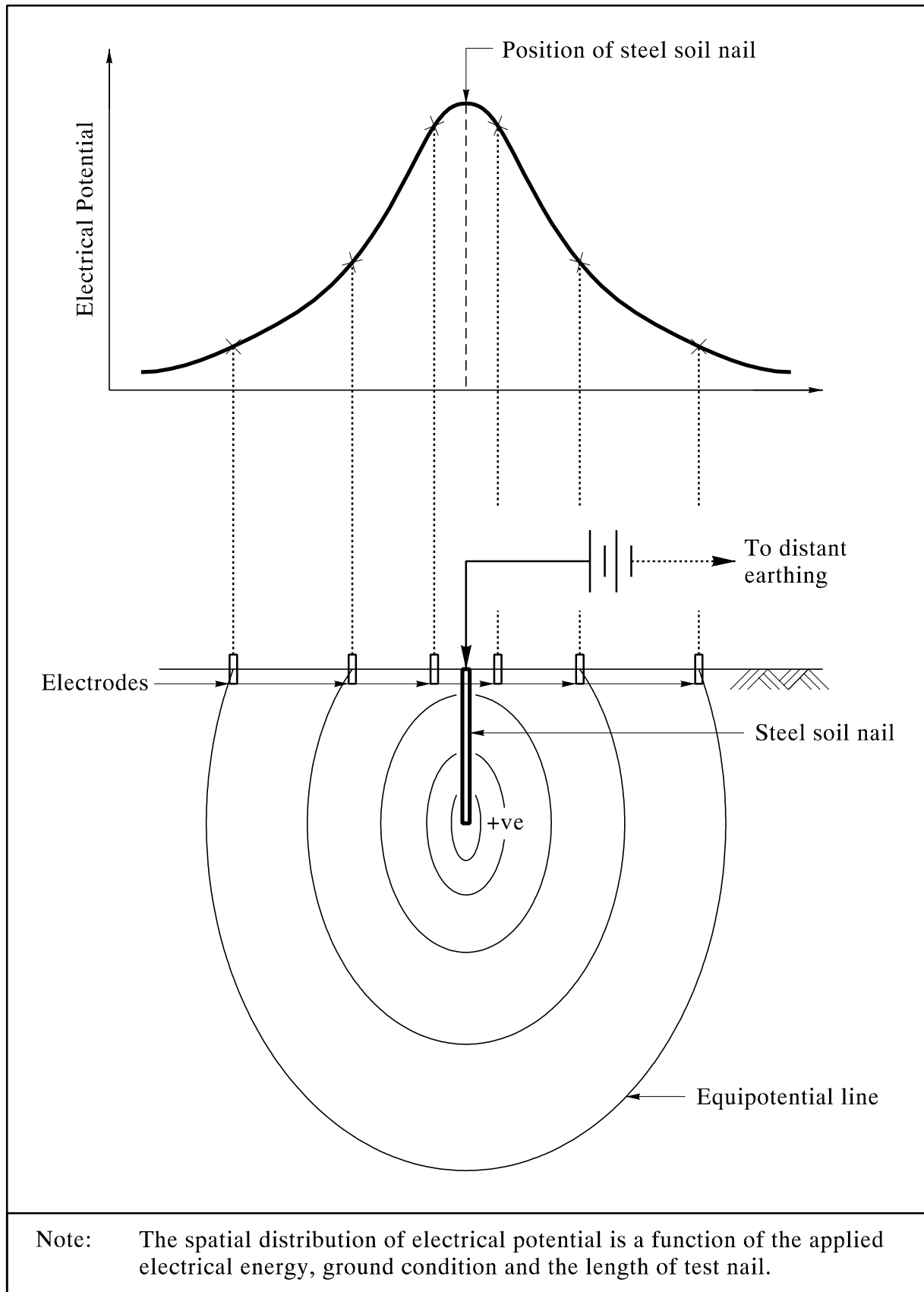


Figure 6 - Spatial Distribution of Electrical Potential Around a Steel Soil Nail of a Given Length

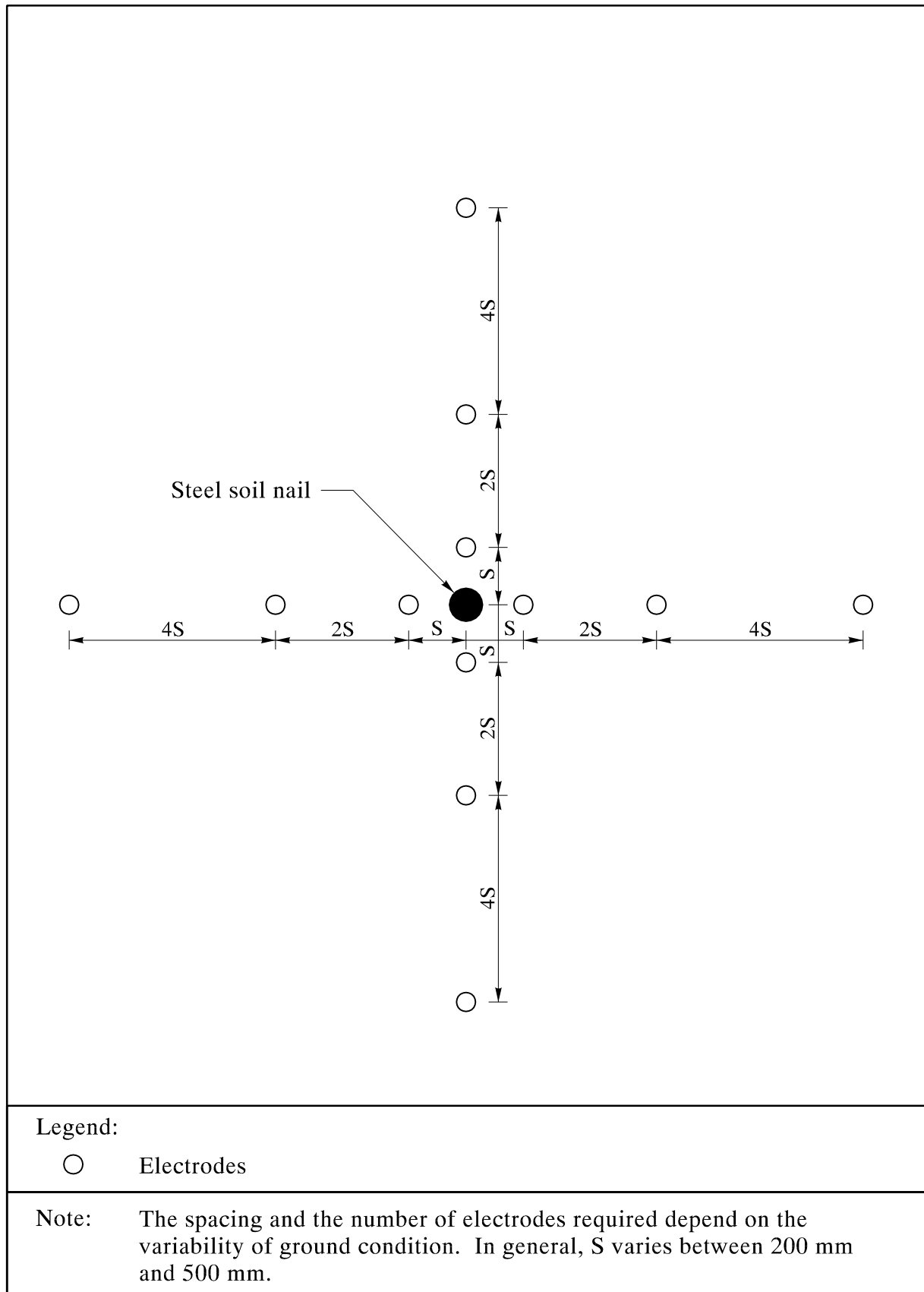


Figure 7 - Schematic Diagram Showing the Layout of Electrodes Around a Steel Soil Nail

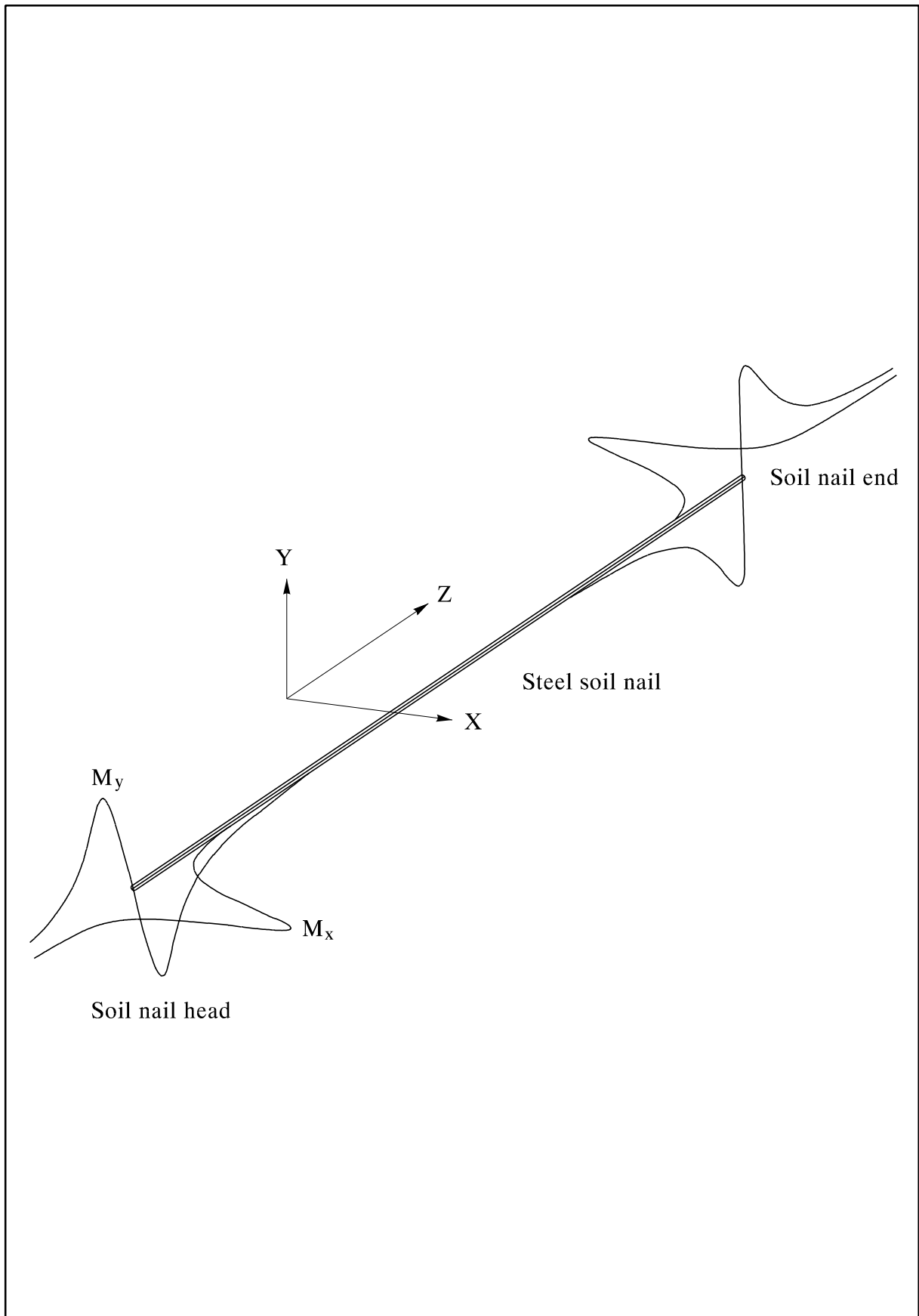


Figure 8 - Theoretical Magnetic Vector Profiles of a Steel Soil Nail

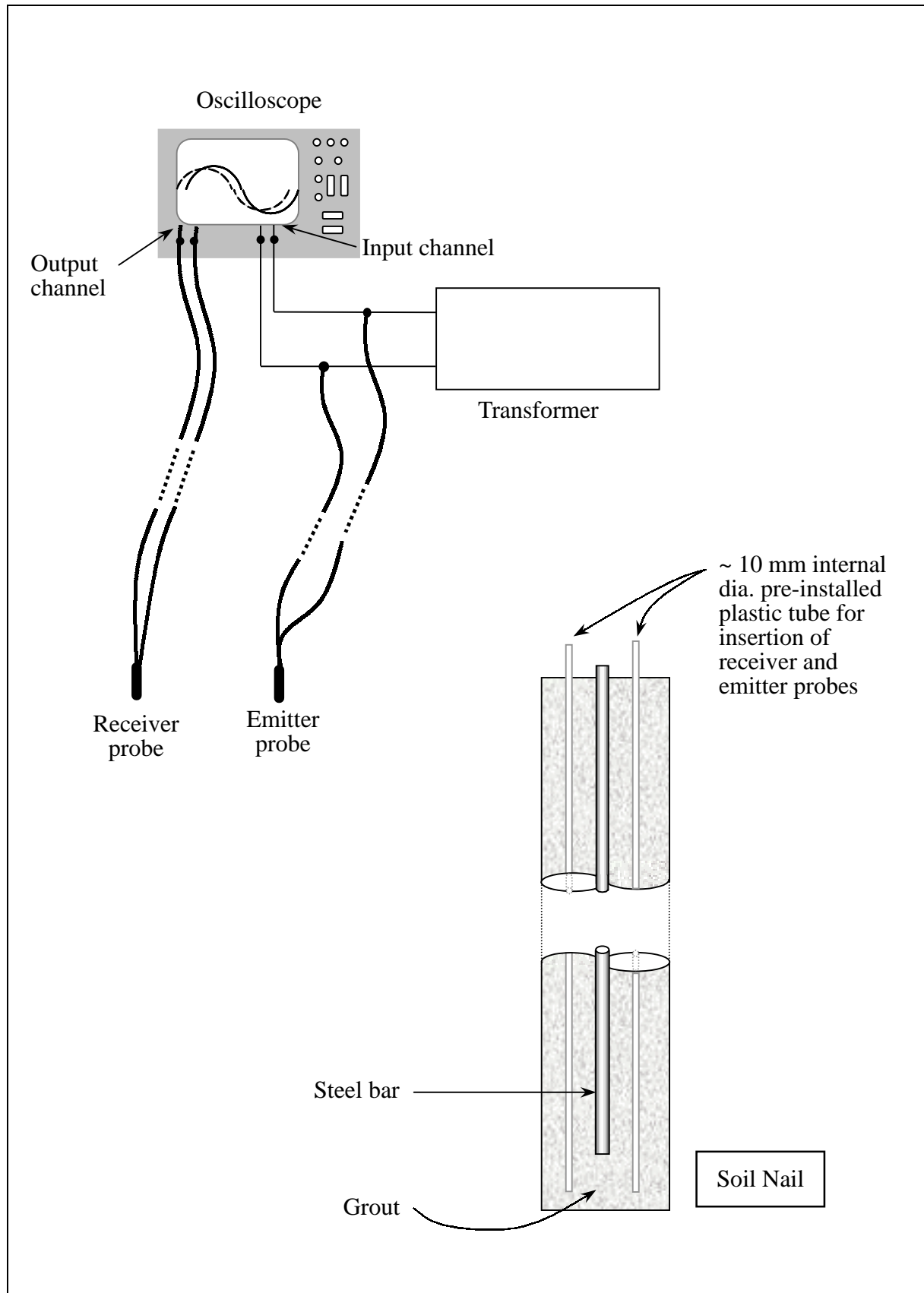


Figure 9 - Schematic Diagram Showing the Set Up of the Electro-magnetic Induction Testing Method

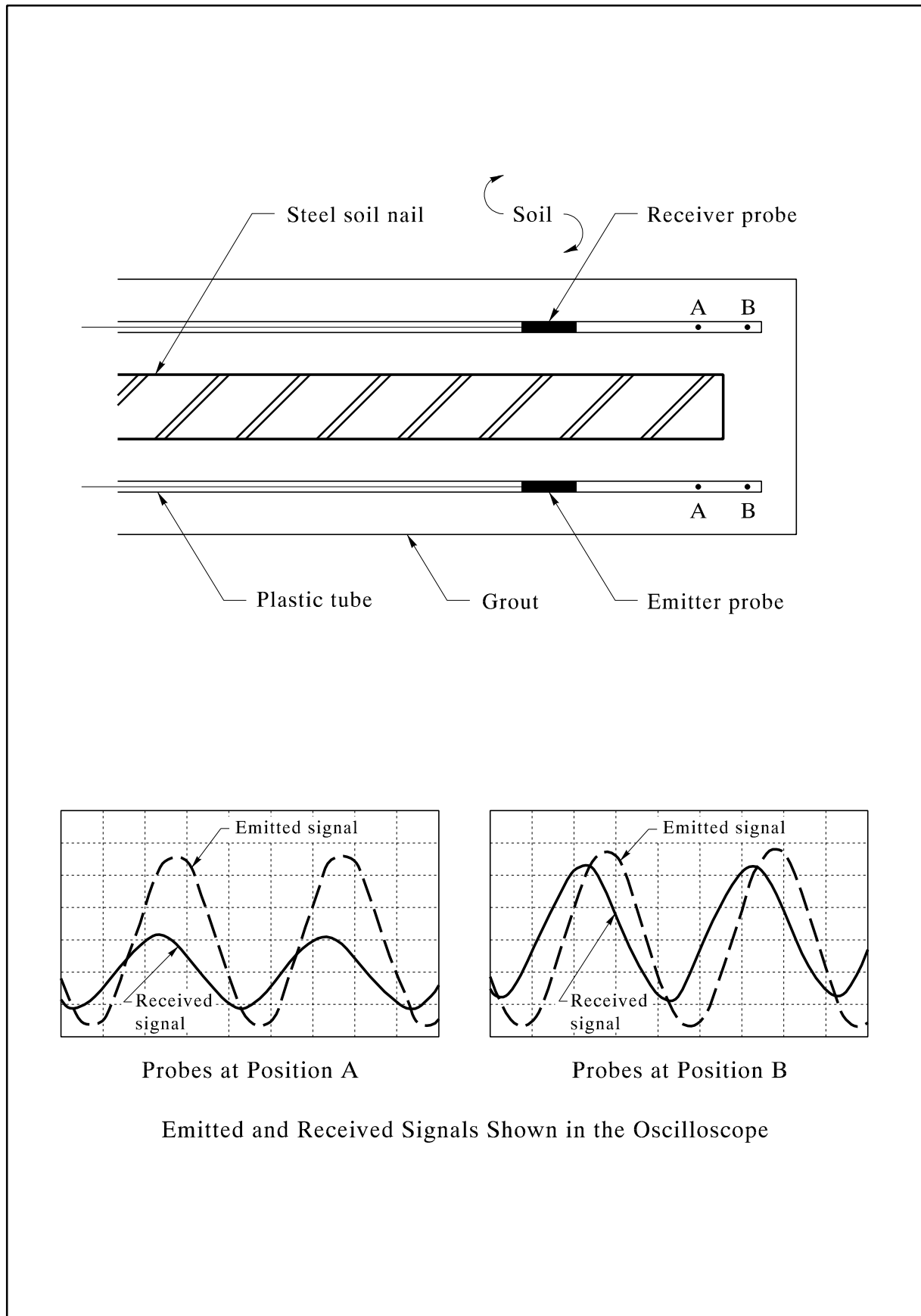


Figure 10 - Principle of the Electro-magnetic Induction Method

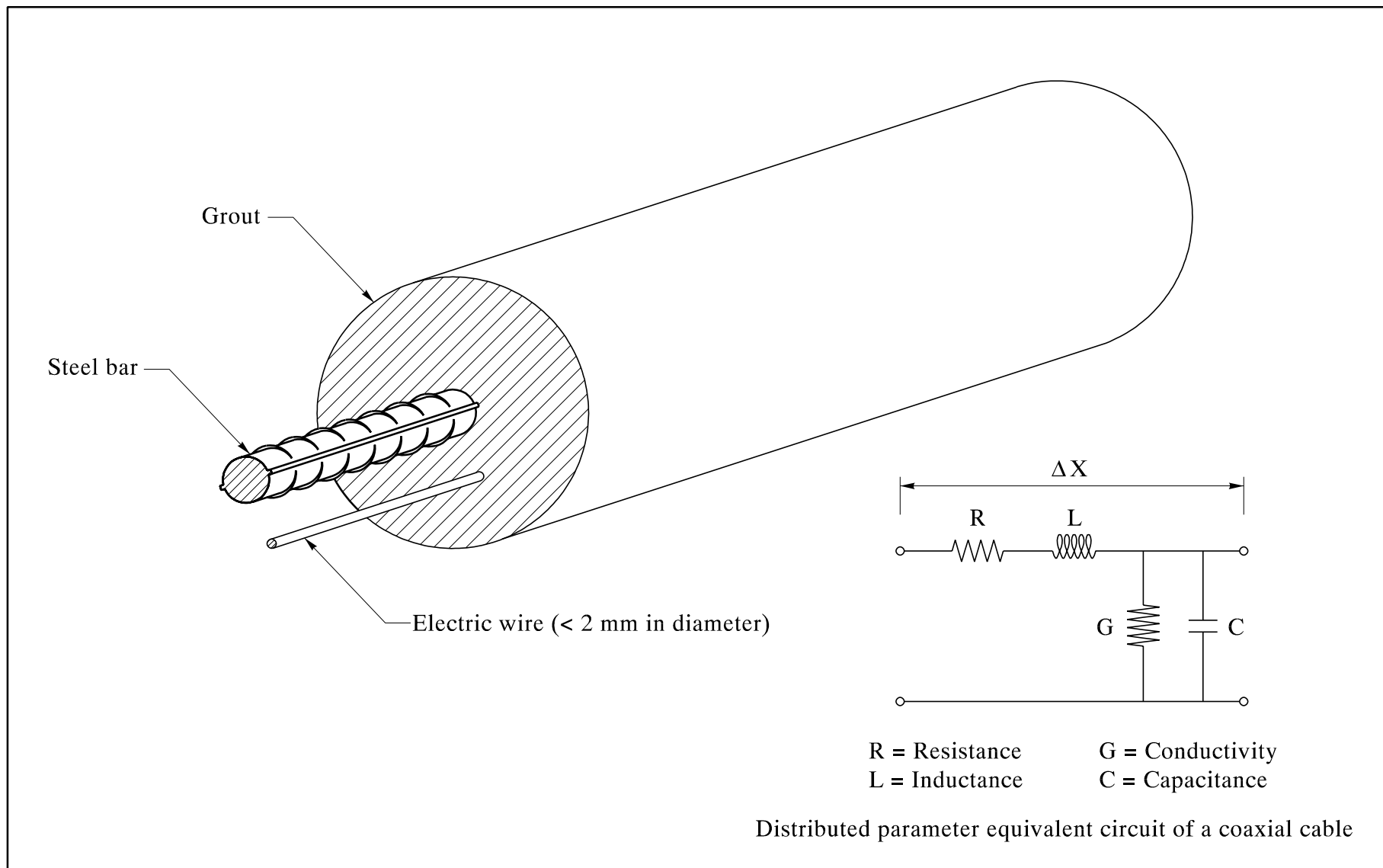


Figure 11 - Model of Steel Soil Nail as a Coaxial Cable

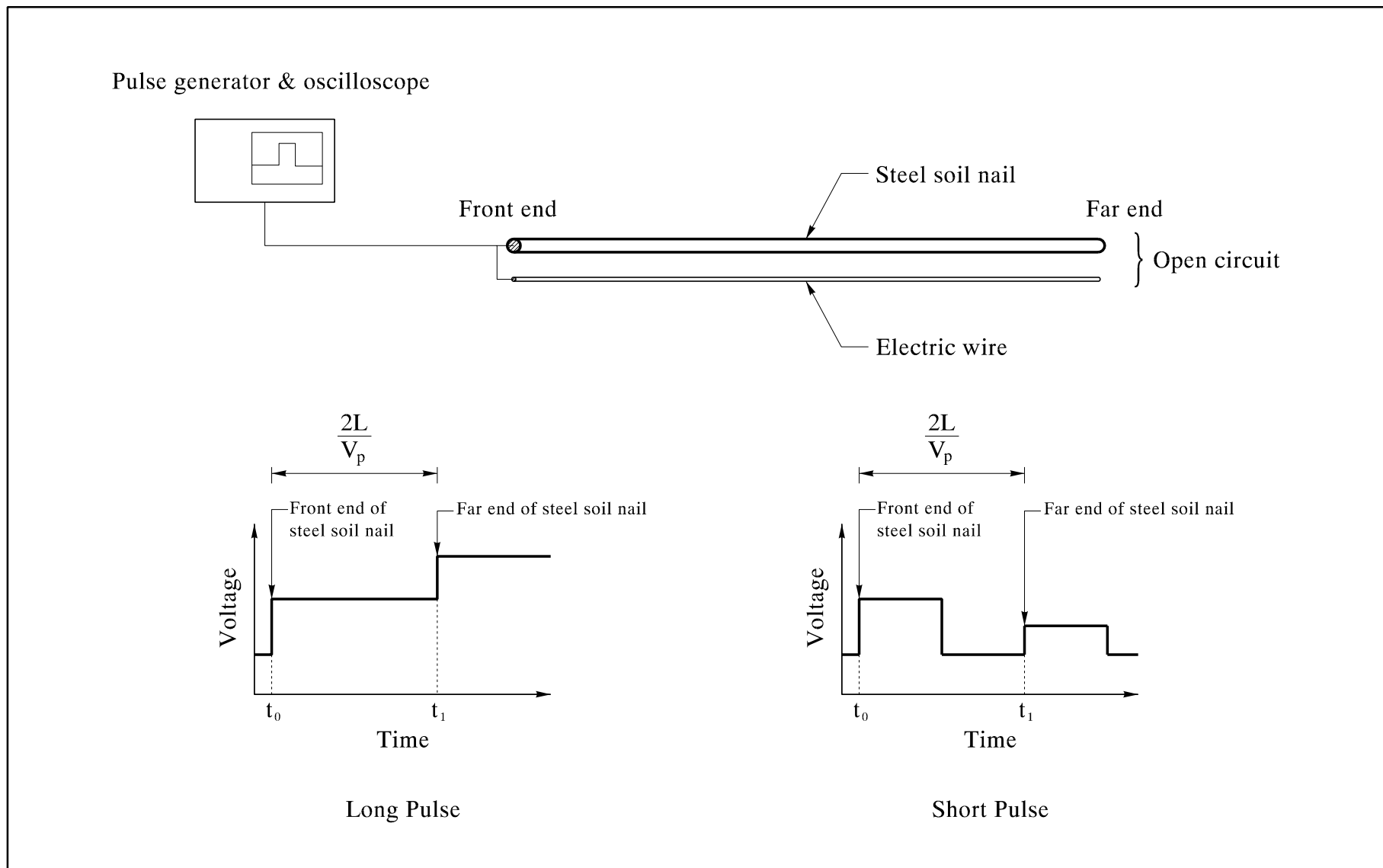


Figure 12 - Theoretical TDR Response from a Steel Soil Nail with Electric Wire (Open Circuit at Bar End)

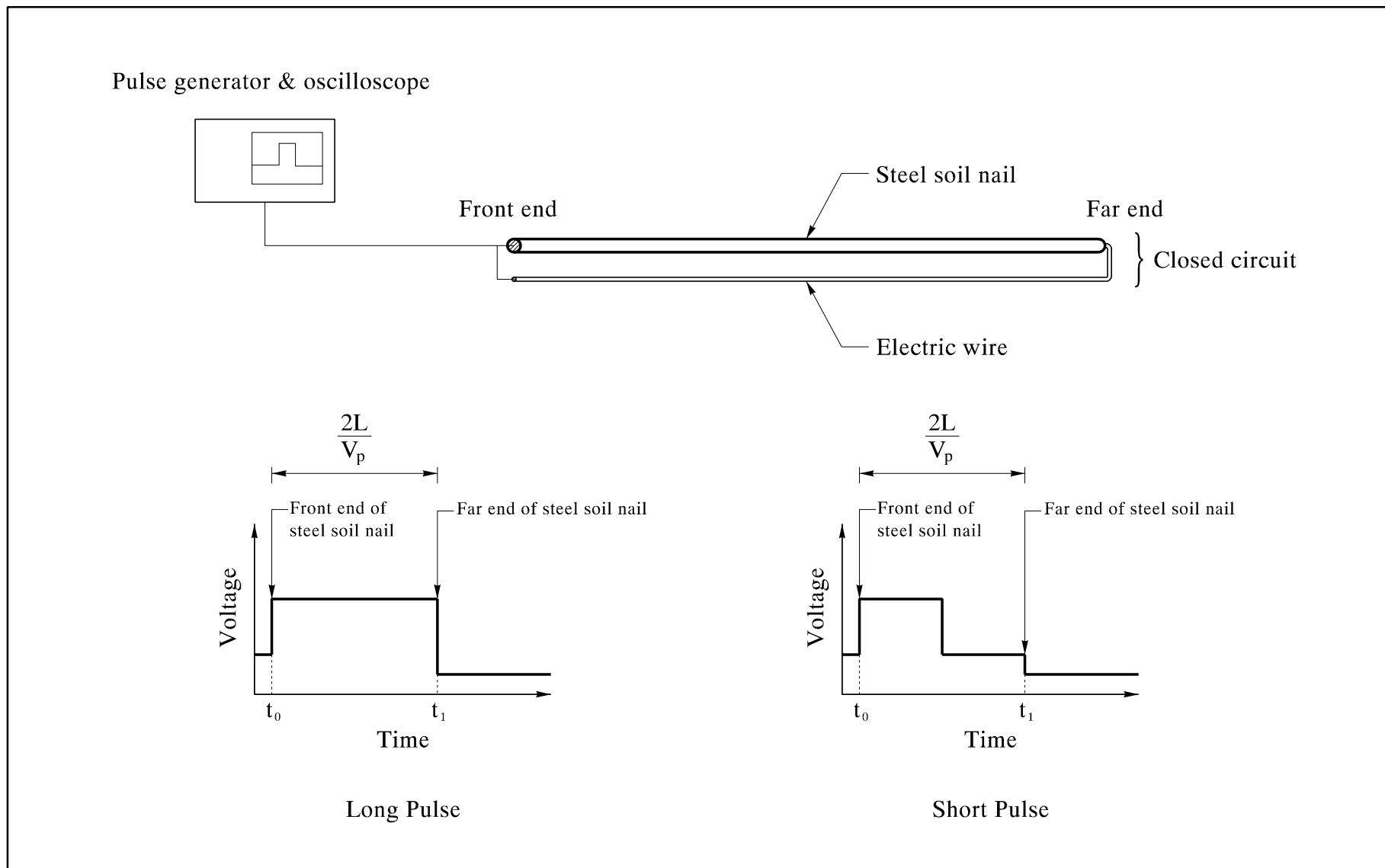
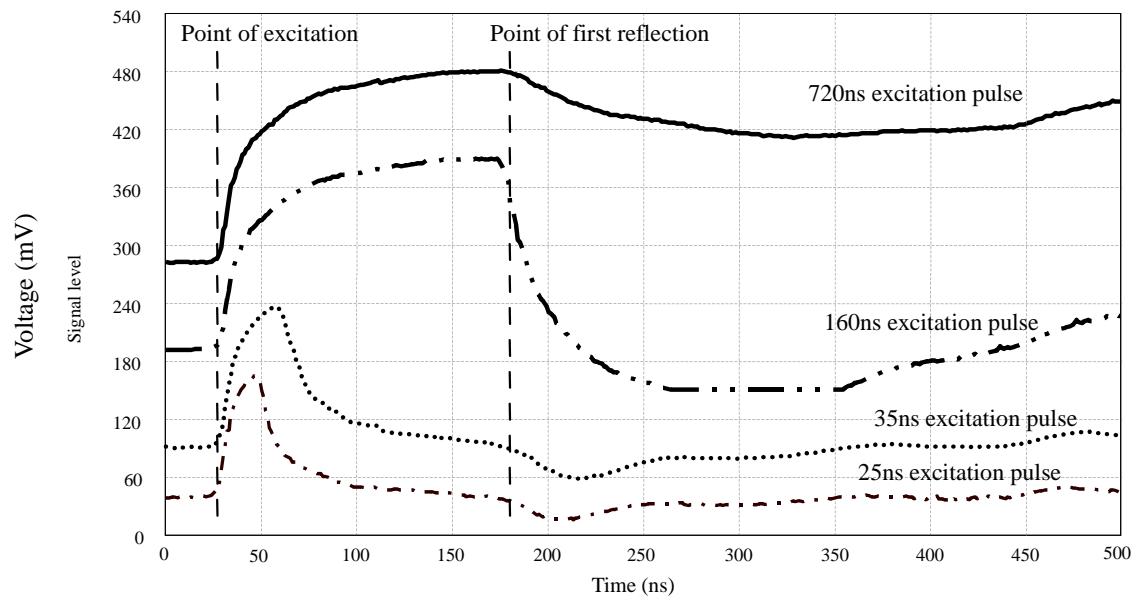
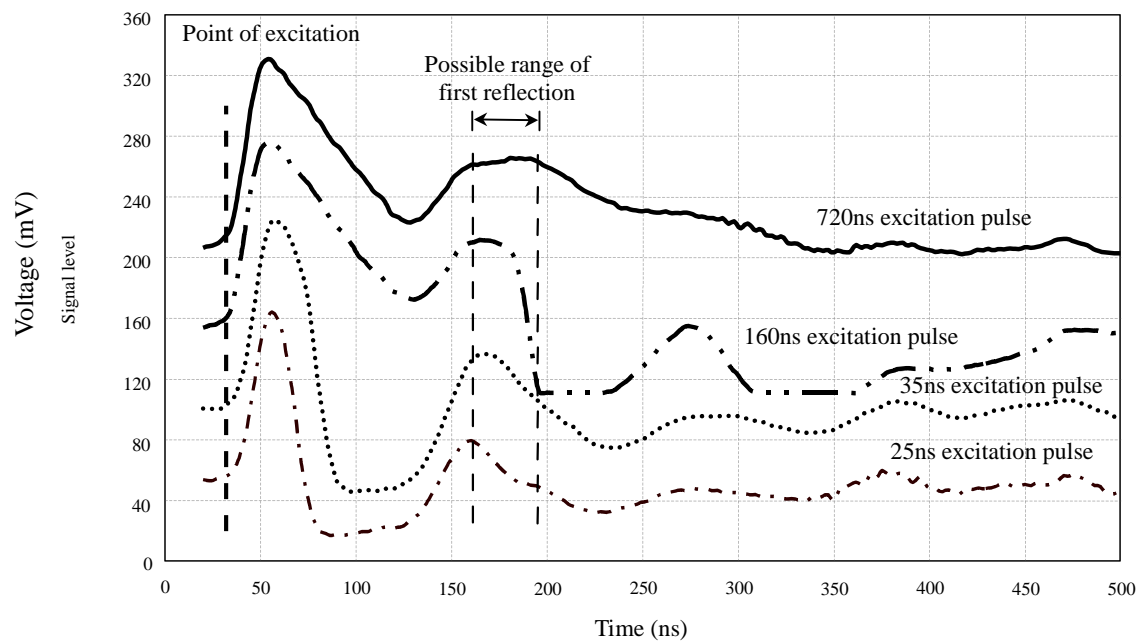


Figure 13 - Theoretical TDR Response from a Steel Soil Nail with Electric Wire (Close Circuit at Bar End)



(a) With Electric Wire



(b) Without Electric Wire

Figure 14 - Comparison Between TDR Responses from a 6 m Long Steel Soil Nail with and without an Electric Wire

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Plate 1 - Inserting the Steel Soil Nail with the Plastic Tube into a Drillhole



Plate 2 - Measuring the Length of Drillhole by Inserting a Flexible Plastic Rod into the Plastic Tube



Plate 3 - Drilling Rig Equipped with the DPM



Plate 4 - Drilling Control and Operation Panel with DPM Pressure Sensors



Plate 5 - Striking the Steel Soil Nail by a Light Hammer



Plate 6 - One of the Electrodes Implanted in the Vicinity of the Installed Soil Nail



Plate 7 - Set Up of the Test Using the Mise-a-la-Masse Method



Plate 8 - Inserting the Magnetometer into a Drillhole in the Vicinity of the Test Nail

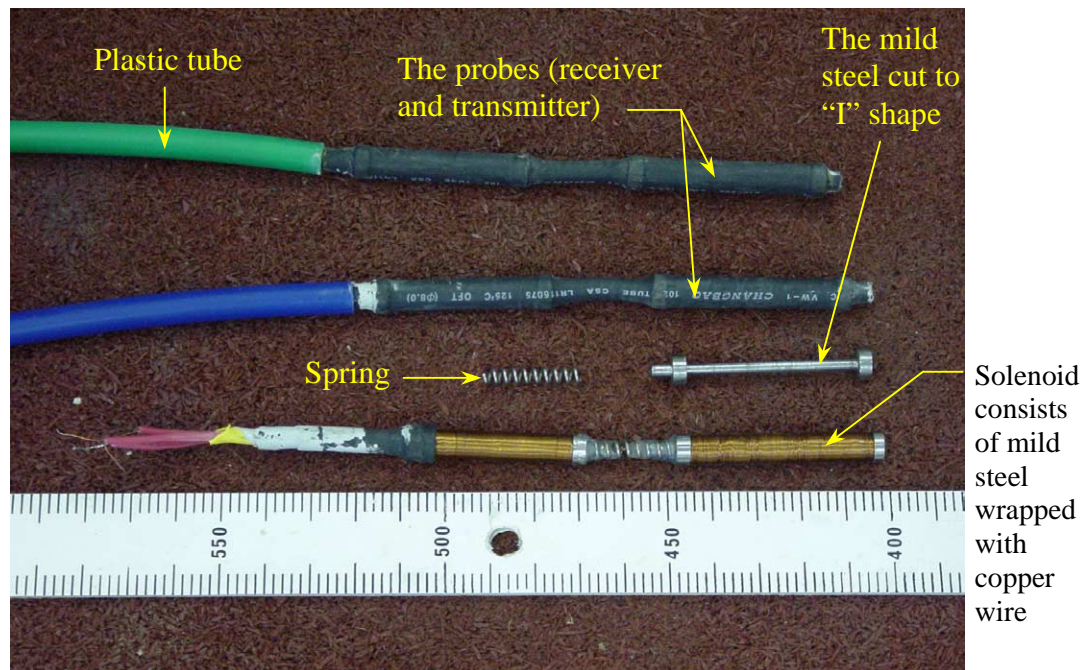


Plate 9 - Details of Probes



Plate 10 - Inserting the Probes into Two Pre-installed Plastic Tubes

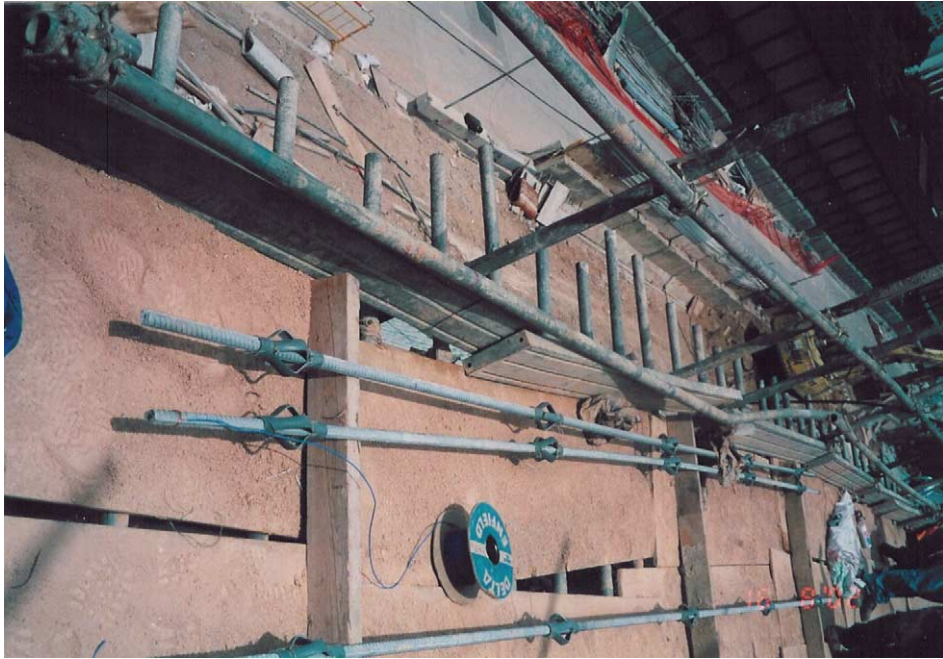


Plate 11 - Fixing of Electric Wire along a Steel Soil Nail



Plate 12 - Connection Details of a Pulse Emitter and Receiver at a Nail Bar Head



Plate 13 - Set Up of the TDR Instrument



Plate 14 - Stitch Drilling around a Steel Soil Nail



Plate 15 - Over-coring of a Steel Soil Nail



Plate 16 - A Steel Soil Nail Remained in the Casing after Over-coring

APPENDIX A

TEST PROCEDURE OF DIFFERENT TESTING METHODS

A.1 TEST PROCEDURE OF SONIC ECHO METHOD

- (i) Ensure the head of the test nail bar be accessible and free from loose materials and water.
- (ii) Mount the sensor (accelerometer) on either the test nail bar head or grout annulus.
- (iii) Set up the apparatus for recording and displaying response received.
- (iv) Strike the nail bar head by a light hand-held hammer.
- (v) Identify the responded time from the nail end and estimate the length of the nail bar based on assumed propagation velocity of stress wave (either by calibration or theoretical derivation).

A.2 TEST PROCEDURE OF MISE A-LA-MASSE METHOD

- (i) Select some soil nails of known lengths for calibration.
- (ii) Ensure the head of the test soil nail bar to be accessible and free from loose materials and grease.
- (iii) Install electrodes in the vicinity of the soil nail bar. The number and spacing of the electrodes to be installed depend on the sensitivity of the electrical potential with distance from the nail bar.
- (iv) Apply an electrical potential to the nail bar by connecting the nail head to one end of a battery and the other end to a distant earthing point.
- (v) Measure the electrical potential of each electrode.
- (vi) Repeat steps (ii) to (v) for test nails and determine the length of the test nail by comparing the potential distribution of a suitable template obtained through steps (i) to (v).

A.3 TEST PROCEDURES OF MAGNETOMETRY

There are two sets of test procedures. One is desirable for testing of a particular soil nail whereas the other one is suitable for testing of a group of soil nails.

Procedure A: for a particular nail:

- (i) Drill a hole parallel and in the vicinity of the test nail. The separation between the drillhole and the test nail should be about 300 mm to 500 mm, and the length of drillhole should be longer than the anticipated length of the soil nail by at least 1 m. The size of the drillhole should be large enough to accommodate a PVC pipe of minimum 55 mm internal diameter.

- (ii) Insert the magnetometer into the PVC pipe. Measure and record the Earth's magnetic field as the magnetometer moves along the pipe until it reaches the end of the pipe.
- (iii) Repeat the measurement and recording process as the magnetometer moves away from the pipe end until it reaches the top of the pipe.
- (iv) Analysing the fluctuation of the measured Earth's magnetic field to determine the locations of couplers and the end of steel soil nails.

Procedure B: for a group of nails:

- (i) Drill a hole parallel and in the centre of a group of test nails. In general, a drillhole can serve nails within a radius of about 2 m. The length of drillhole should be longer than that of the longest soil nails by at least 1 m. The size of the drillhole should be large enough to accommodate a PVC pipe of minimum 55 mm internal diameter.
- (ii) Polarised the test nail by putting a magnet on the nail head.
- (iii) Insert the magnetometer into the PVC pipe. Measure and record the Earth's magnetic field as the magnetometer moves along the pipe until it reaches the end of the pipe. It is preferable to have measurement in an intermittent manner (say in an increment of about 0.1 m).
- (iv) Repeat step (ii) by reversing the direction of the magnet.
- (v) Repeat the measurement and recording process as the magnetometer moves away from the pipe end until it reaches the top of the pipe.
- (vi) Repeat steps (i) to (v) for other test nails.
- (vii) Analysing the fluctuation of the measured Earth's magnetic field to determine the locations of couplers and the end of steel soil nails.

A.4 TEST PROCEDURE OF ELECTRO-MAGNETIC INDUCTION METHOD

- (i) Probe the plastic tubes by a flexible rod to make sure no blockage of the tubes.
- (ii) Apply a voltage into the emitter probe.
- (iii) Insert simultaneously the emitter and receiver probes into each of the plastic tubes.
- (iv) Move the probes simultaneously along the plastic tubes until a noticeable rise in voltage in the receiver probe is observed in the oscilloscope.
- (v) Move the probes forward and backward to confirm location of the rise in voltage.
- (vi) Record the voltages taken by the oscilloscope and measure the depth of the probes that have been inserted.

A.5 TEST PROCEDURES OF TIME DOMAIN REFLECTOMETRY

There are two sets of test procedures. The first one requires pre-installation of an electric wire wherein the return signal from the nail end can be identified easily, whereas the second one does not require electric wire installation and the return signal is comparatively blurred.

Procedure A (with electric wire installation)

- (i) Select some soil nails of known lengths for calibration of pulse propagation velocity.
- (ii) The head of the steel soil nail shall electrically be accessible. All loose materials shall be removed from the bar head.
- (iii) Connect the TDR instrument to the steel soil nail head and the electric wire.
- (iv) Send a short pulse into the steel soil nail and record the time of reflection (if the wire is electrically in contact with the steel soil nail end, the return signal from the nail end should go down and vice versa).
- (v) Send a long pulse into the steel soil nail and record the time of reflection (if the wire is electrically in contact with the steel soil nail end, the return signal from the nail end should go down and vice versa).
- (vi) Determine the average propagation velocity of the pulse from the results obtained in steps (iv) and (v).
- (vii) Repeat steps (ii) to (v) for steel soil nail to be tested and estimate its length by using the calibrated propagation velocity.

Procedure B (without electric wire installation)

- (i) Select some soil nails of known lengths for calibration of pulse propagation velocity.
- (ii) The head of the steel soil nail shall electrically be accessible. All loose materials shall be removed from the bar head.
- (iii) Connect the TDR instrument to the steel soil nail head.
- (iv) Send a short pulse into the steel soil nail and record the time of reflection.
- (v) Send a long pulse into the steel soil nail and record the time of reflection.
- (vi) Determine the average propagation velocity of the pulse from the results obtained in steps (iv) and (v).
- (vii) Repeat steps (ii) to (v) for steel soil nail to be tested and estimate its length by using the calibrated propagation velocity.