Review of Investigation Methods to Determine Pile Lengths

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ABSTRACT: With rapid urbanisation, there are several constraints for the use of aboveground space, as a result, rail infrastructures are often located underground. Inevitably, underground obstruction such as pile foundations will be encountered during tunnelling works. Due to the incomplete or lack of as-built information, pile length investigations must be conducted to detect any potential obstructions in advance to construct the underground rail lines safely. However, there is insufficient information in the literature to choose the suitable method for pile length investigation. Land Transport Authority projects have employed different methods to investigate the pile length depending site constraints and type of foundation. This paper reviews the effectiveness and reliability of different methods that are commonly employed in Singapore and can serve as a useful guide in the selection of method(s) for pile length investigation.

1 INTRODUCTION

With rapid urbanisation and scarcity of land, underground space is often utilised for the development of infrastructure projects. The foundation pile of exiting or demolished structures can be an obstruction to underground rail projects and due to the incomplete or lack of as-built information, there is a need to detect these obstructions in advance to construct the underground rail lines safely. Upcoming rail lines (e.g. Cross Island Line, CRL) and other underground projects are expected to encounter similar obstructions because of the our densely urbanised city, hence it is timely to review the appropriate pile length investigation method to be employed.

Determination of pile length under the existing structure is challenging because the investigation method must be non-destructive to maintain the integrity of the structure. There are several methods available in the literature for pile length investigation. The methods for foundation investigation can be broadly classified into Direct and Indirect methods. Direct methods such as (i) Low Strain Integrity testing and (ii) Sonic logging testing require access to the pile where accelerometers are attached close to the top of the pile. Indirect methods are based on geophysics and require a borehole adjacent to the pile to emit and/or receive signal. The indirect geophysical methods available include (i) Parallel Seismic, (ii) Magnetometer, (iii) Borehole Radar and (iv) Borehole Electrical Resistivity.

This paper focuses on three geophysical methods that are commonly employed in Singapore, (i) Parallel Seismic, (ii) Magnetometer and (iii) Borehole Radar. Details of the three methods are discussed in the following sections. Geophysicists and users must understand the method, examine and appreciate the in-situ ground conditions and constraints before selecting the method.

2 PILE LENGTH DETERMINATION UNDER EXISTING STRUCTURES

2.1 Parallel Seismic (PS)

Parallel seismic method works based on the contrast in the material elastic modulus (E) of the pile and its surrounding soil (e.g. between E_{Pile} and E_{Soil}). Seismic wave reflects when it encounters a change in impedance at the interface of pile and soil and it travels at a much faster speed in pile than in soil. Pile impedance ($Z_{PS} = EA/c$) is a function of the wave speed (c), E and pile cross-sectional area (A) while the velocity of stress wave propagation ($V^2 = E/\rho$) is a function of E and density (ρ).

As shown in Figure 2.1, in a parallel seismic test, the ideal way to generate the seismic wave is by impacting the pile head directly. Refracted waves along the pile are detected by receiver such as hydrophones or geophones placed in the borehole adjacent to the target pile and the signal arrival time is recorded in a seismometer at the surface. A series of data at equal intervals of not more than 0.5 m are recorded along the borehole which extends at least 5 m beyond the expected pile toe. However, due to site constraints, the pile head might not be accessible, Figure 2.2 shows the setup of parallel seismic test on site where the pile is not exposed and impact is generated on the column that is structurally connected to the target pile.

Multiple sets of data might be required to increase the signal to noise ratio by stacking and amplifying the amplitude exponentially with time. Reported data are presented in a plot of arrival time versus the receiver depth for pile toe interpretation. The recorded data can be translated into wave propagation velocity and the stark contrast between the propagation velocity thru the pile (higher) and soil (lower) is expected hence a noticeable change in gradient will be observed.

Pile toe can be interpreted at the point where the change of gradient is observed from the plot of arrival time versus receiver depth. However, this method of interpretation has reportedly overestimated the true pile length. A recent study (Liao et al, 2005) had proposed a method to enhance the accuracy by introducing a correction factor to cater for the distance between the pile and borehole. The correction factor proposed by Liao et al (2005) is given by, $R = F(V_1/V_1 - V_2) - X(V_2/V_1 - V_2)$ where V_1, V_2 are propagation velocity in pile and in soil respectively and $F = (D^2 + X^2)^{1/2}$ are geometry parameters (Figure 2.3).

The premise of parallel seismic method depends on the availability of contrast in E between the pile toe and the surrounding material, which is limited when the pile is socketed into rock. Increasing the distance from the borehole to the target pile will increase the error of the interpreted pile length as reported by Liao et al (2005). According to Niederleithinger (2012), the distance between borehole to pile can be up to 3 m.

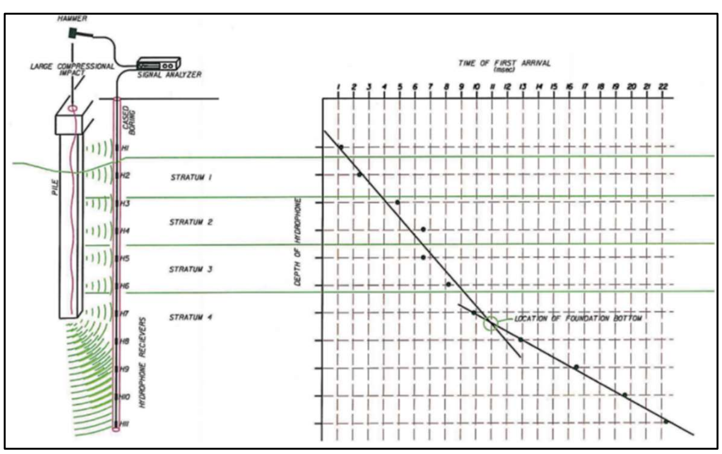


Figure 2.1 Schematic Illustration of Parallel Seismic Method

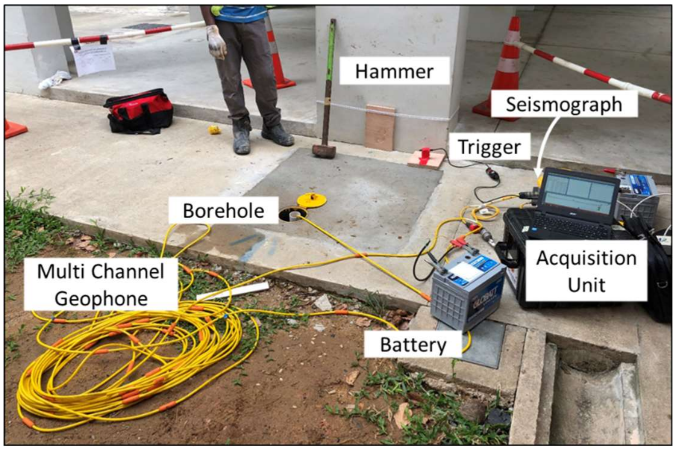


Figure 2.2 Setup of Parallel Seismic Test

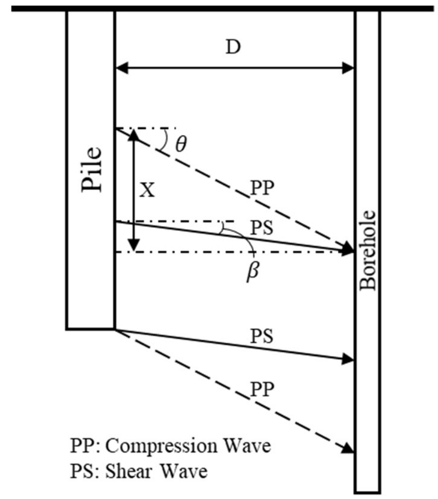


Figure 2.3 Travel Paths of Stress Waves in a Parallel Seismic Test

2.2 Magnetometer (MNT)

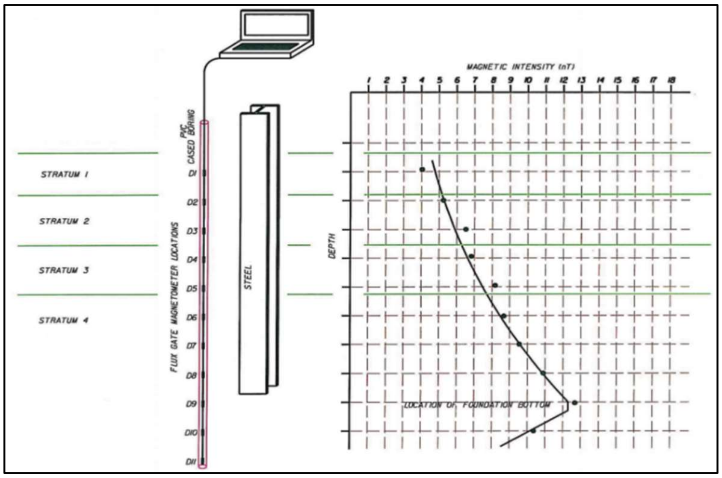
Magnetometer survey measures localized anomalies of the normal field (Earth's magnetic field) caused by the induced magnetic field of ferromagnetic material. The induced magnetic field can either increase or decrease the local magnetic field depending on its direction with respect to the normal field. Anomalous magnetic field of interest is obtained by subtracting the normal field from the observed total magnetic field to produce interpretable data. The magnitude of induced magnetic field depends on the size of the ferromagnetic material in the pile and the signal decays rapidly with increasing distance from the pile.

Figure 2.5 shows a borehole magnetometer survey on site, where a magnetometer is used to detect the magnetic field induced by the steel reinforcement in the concrete pile as it traverses along the borehole and recorded in the recording device. A Fluxgate magnetometer that measures the magnetic field in three components (x-y-z) is commonly used, continuous data will be recorded and the magnetic field of interest will be plotted against the depth of the borehole which extends at least 5 m beyond the expected pile toe.

The magnetic field data can be interpreted using the vertical derivative method that is based on the theoretical response of magnetic dipole (Telford et al, 1976). Magnetic dipole can represent many types of pile such as steel pile and the reinforcement within concrete pile. As shown in Figure 2.6, the intensity or magnitude of the vertical component shows local peaks near the ends, while the horizonal component shows local extreme values near the ends. The vertical derivative value will then be used for interpreting the depth of pile toe. The characteristic of having the peak (absolute) value near the ends of the pile makes a simple interpretation criterion of the pile toe.

Pile toe recognition of magnetometer test relies on availability of continuous reinforcement through the entire length of the pile and when minerals such as magnetite are found in the surrounding ground, it will also induce a magnetic field that may complicate the interpretation. However, without the presence of ferromagnetic minerals, the magnitude of the induced magnetic field would be insignificant and will not interfere with the test.

The intensity or amplitude of magnetic anomaly is given by $T = M/r^n$, where M is the magnetic moment, r is the distance between the borehole to the pile and n is the rate of decay with distance ($n = 3$ for dipole). Although, magnetometer test can be applicable up to 3 m away from the pile under certain condition, it should be noted that the amplitude of signal decays at cube rate and depending on the source amplitude, the efficacy range can increase or decrease accordingly.



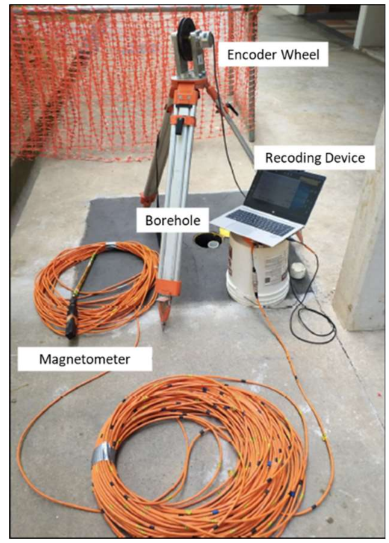


Figure 2.4 Schematic Illustration of Magnetometer Method

Figure 2.5 Setup of Magnetometer Test

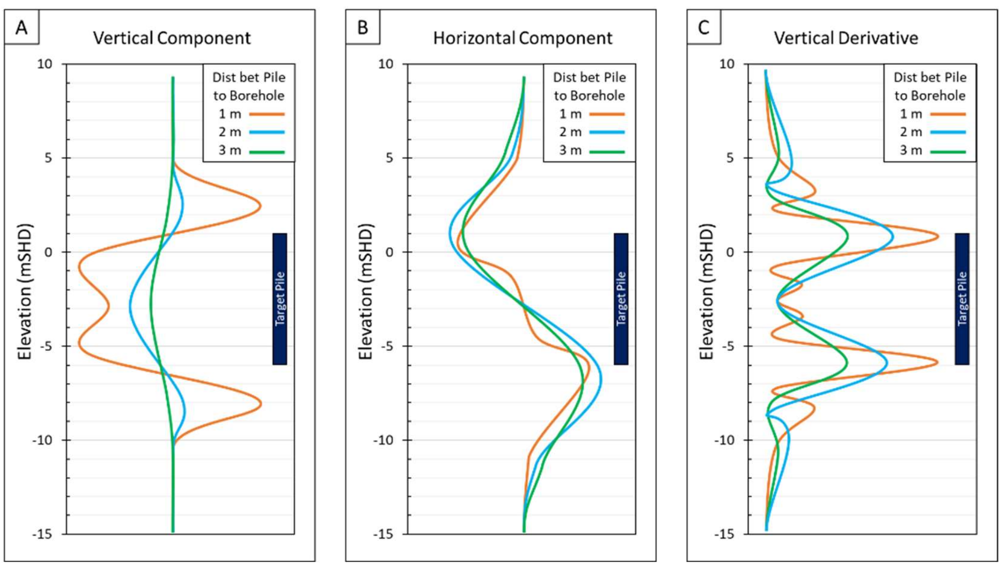


Figure 2.6 Induced Magnetic Field at 1m, 2m and 3m away from Target Pile; A. Vertical Component; B. Horizontal Component; C. Vertical Derivative (absolute values) of Vertical and Horizonal Component

2.3 Borehole Radar (BHR)

Borehole Radar adopts the same concept as Ground Penetrating Radar (GPR) that is used for subsurface investigation. Radio Detection and Ranging (Radar) is an electromagnetic (EM) method that employs EM wave to detect the presence of an object by transmitting pulses and recording the reflection and/or refraction of the EM waves. Reflection of EM waves occurs when there are abrupt changes in the dielectric properties, usually at the interface of an object. Understanding the velocity of EM wave propagation and the EM impedance across the interface of the target material is key to employ the test successfully. The fundamental properties that govern the behaviour of EM waves are dielectric permittivity (ε), electrical conductivity (σ) and magnetic permeability (μ), which together defines the EM wave impedance (Z) (Von Hippel, 1954).

In borehole radar test, an omnidirectional antenna that consists of both transmitter and receiver, separated by a fixed distance is commonly used. EM pulse generated by the transmitter propagates radially into the surrounding material. EM wave reflects when it encounters a change in physical property and signal will be recorded in the recording device at the surface. Refer to Figure 2.7 for the schematic set up of borehole radar test and Figure 2.8 for the setup on site. A continuous set of data will be recorded as the antenna traverses along the borehole which extends at least 5 m beyond the expected pile toe.

Table 1 Effect of Radar Parameters on Operational Performance

Radar Parameters	Dielectric Constant		Electrical Conductivity		Antenna Frequency		Remarks
	Low	High	Low	High	Low	High	
Propagation Velocity	Fast	Slow	-	-	-	-	Velocity is high in materials with low dielectric constant (i.e. dry sand), and low in saturated materials (i.e. clayey soil).
Attenuation	-	-	Low	High	-	-	Signal attenuation is strongly influenced by electrical conductivity.
Penetration Distance	-	-	Long	Short	-	-	High conductivity environment has higher attenuation thus shorter penetration distance.
Wavelength	-	-	-	-	Long	Short	Short wavelengths have shallower penetration depth and the converse is true.
Resolution	-	-	-	-	Low	High	Short wavelength yields higher resolution radargram and the converse is true.

Table 1 shows the effect of Radar parameters on operational performance. The choice of antenna frequency has a direct impact on both the resolution and depth of penetration. A higher frequency antenna emits waves with a shorter wavelength, as a result, the waves have a better chance of intercepting smaller objects (higher resolution) than the lower frequency antenna. However, with each interception, the signal will be attenuated, therefore the penetration depth is consequentially shallower.

Figure 2.9 shows the illustration of borehole radar reflecting off different reflectors and radargram shows the reflected energy is recorded in the function of time and depth (Johnson and Joesten, 2003). Radargram provides an image of the signal received radially and will be altered depending on the shape and relative location of the reflector to the borehole. For pile toe investigation, the pile is expected to produce a planar feature reflection at an offset from the borehole and the pile toe may be interpreted at the depth where the reflected energy diminishes abruptly. Refer to the report by USGS (Johnson and Joesten, 2003) for a detailed write up on the analysis of borehole radar reflection data.

Attenuation of EM signal is governed by electrical conductivity and relative dielectric permittivity. The attenuation or dispersion of EM wave is commonly referred to as dielectric loss and it is considered negligible if the conductivity of the material is less than 10 milli-Siemens/meter (mS/m), as it is for many geologic materials. The amplitude (A_o) of the original EM waves decreases exponentially with propagation distance (d) according to $A = A_o e^{-\alpha d}$, with the attenuation constant, $\alpha = 0.5\sigma(\mu/\varepsilon)^{0.5}$ (Theimer et al, 1994).

The major limitation of borehole radar is the limited applicability in clayey, saturated and saline environment. Clayey soil and water will reduce the propagation velocity and increase the rate of signal attenuation, resulting in a reduced depth of penetration. Radar signal will also be rapidly attenuated in saline water (e.g. sea/brackish water) because of its high conductivity. Under undesirable conditions, radar signal may be masked and reflection signal (if any) will not be observed on the radargram.

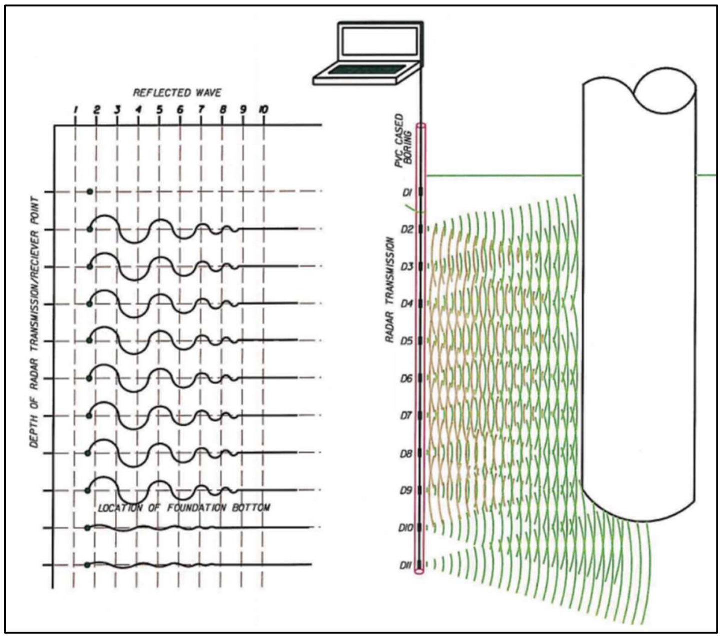


Figure 2.7 Schematic Illustration of Borehole Radar Method

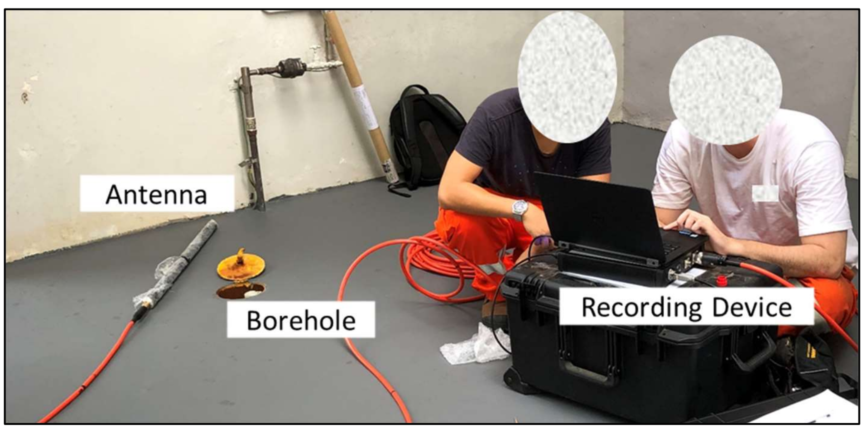


Figure 2.8 Setup of Borehole Radar Test

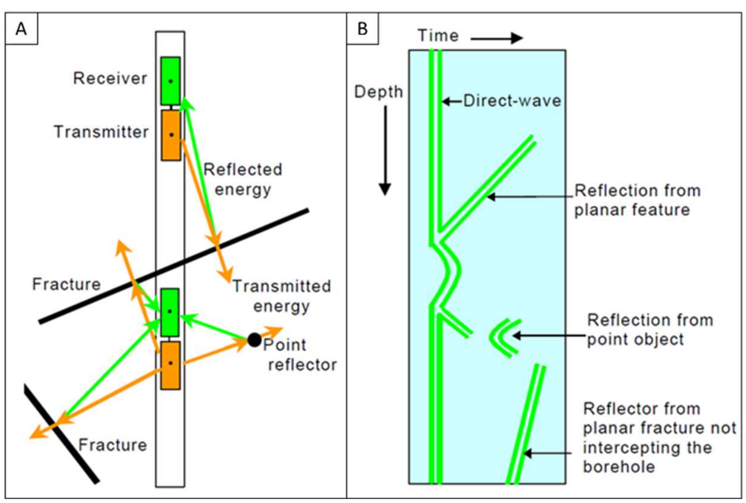


Figure 2.9 Illustration of EM Waves Reflection in Borehole Radar Test; A. Borehole Radar Set Up with Different Reflectors; B. Resultant Radargram from Different Reflectors (Johnson and Joesten, 2003)

3 INVESTIGATION RESULTS AND DISCUSSIONS

More than 100 test results from past LTA projects where as-built pile length information is available were used in this study. The pile lengths were not known to the sub-contractors and results were gathered from tests conducted by different sub-contractors with varying site conditions. All the boreholes prepared were positioned as close to the target pile as practically possible with an average offset distance of 1.5 m that ranges between 0.6 m to 3.1 m and terminated at least 5m beyond the as-built pile toe level.

Another important aspect in the foundation investigation is the verticality of the borehole, a verticality of borehole between 1 in 50 to 1 in 100 is generally expected and extra effort has been made to keep the verticality within the limits. The geophysicist must consider the expected deviation due to borehole verticality in pile length interpretation.

3.1 Pile Length Interpreted by Parallel Seismic

For parallel seismic method, generating seismic wave by impacting the pile directly is ideal. However, due to site constraints, seismic waves were generated by impacting the nearest column or ground that is connected to the target pile. A separate study was carried out to assess the effect of impacting the pile directly and results appear to be comparable. However, further study is required to ascertain the effects of generating seismic waves have on the interpreted pile length.

A total of 37 parallel seismic tests were conducted to investigate the pile lengths, 35 of which are concrete piles and the remaining are steel piles. Figure 3.1 shows the comparison of test results with as-built pile lengths. More than 90% of the parallel seismic test on concrete pile shows a deviation of $\pm$10% from the as-built length and more than 50% are within $\pm$5% of the as-built length. This observation aligns with Niederleithinger (2012) finding that the distance between pile to borehole may be extended up to 3 m and the expected accuracy may fall within $\pm$10% of the true pile length. All the test results presented are within 3m from the target pile (furthest at 2.6m).

Significant deviation from as-built length is observed when parallel seismic test is carried out on steel pile. Theoretically, parallel seismic is also applicable for steel piles, possible reasons for significant variation in pile length could be (1) the presences of mechanical discontinuity due to corrosion of the pile such that the signal is unable to propagate further; (2) the signal needs to overcome greater attenuation due to scattering and might be completely attenuated before it can propagate to the pile toe.

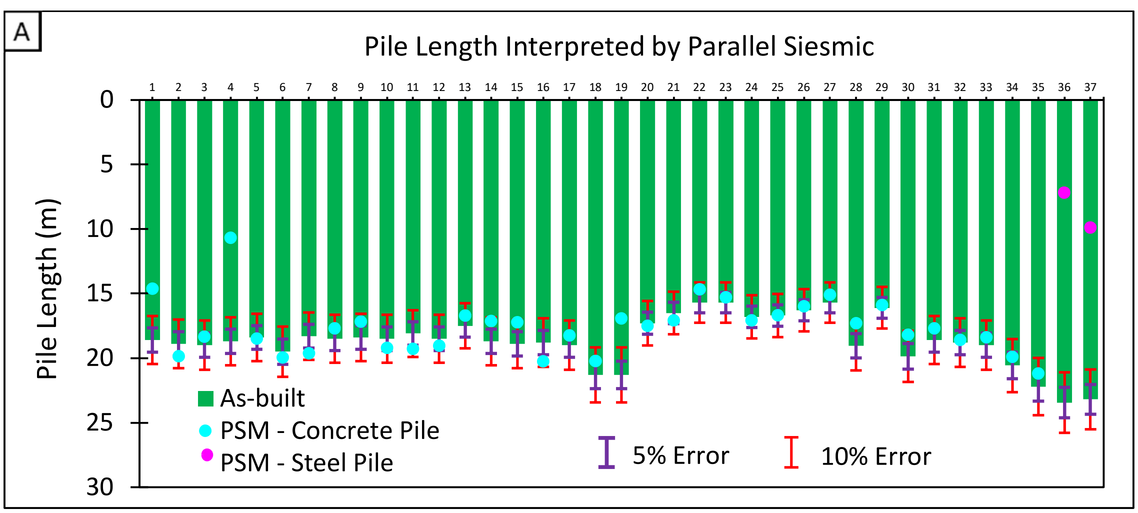


Figure 3.1 Parallel Seismic Test Result; A. Pile Length Interpreted by Parallel Seismic

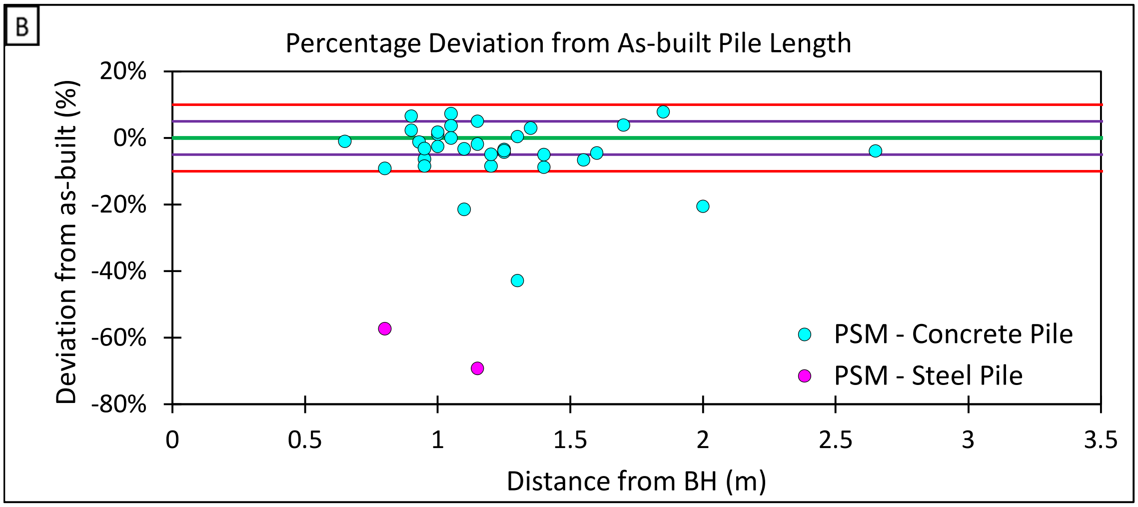


Figure 3.1 Parallel Seismic Test Result; B. Percentage Deviation from As-built Pile Length

3.2 Pile Length Interpreted by Magnetometer

A total of 66 magnetometer tests were carried out to investigate the pile lengths, 32 of which are steel piles and the remaining 34 are concrete piles. The test results on steel pile are analysed separately from those of concrete pile to understand the effectiveness of the method with respect to pile type.

Figure 3.2 shows the comparison of magnetometer test results with as-built pile lengths. For tests on steel piles, more than 90% are within ±10% of the as-built length and 75% are within ±5% of the as-built length.

In the case of concrete piles, reinforcement lengths were interpreted to be approximately 12 m or 18m for some of the piles, which deviates significantly from as-built pile lengths. This suggests that the reinforcement did not extend to the pile toe, whereas tests on RC piles show pile lengths are in reasonable agreement with test results. Magnetometer test relies on magnetic field which does not exist below the available reinforcement in concrete piles. This suggests that magnetometer method can provide reliable results for steel piles and pre-cast concrete piles but should not be applied in bored piles where reinforcement length may not extend to the pile toe.

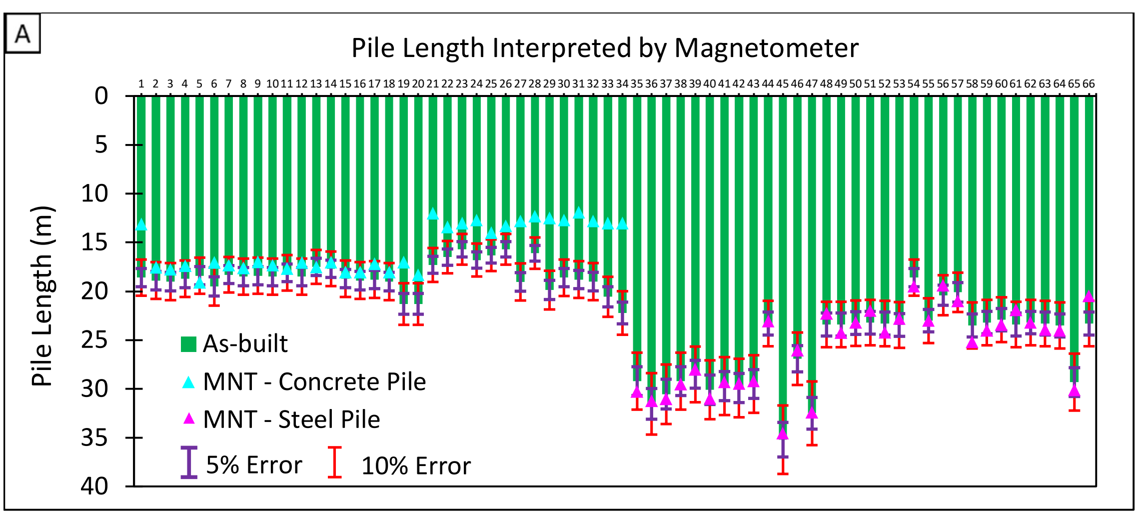


Figure 3.2 Magnetometer Test Result; A. Pile Length Interpreted by Magnetometer ;

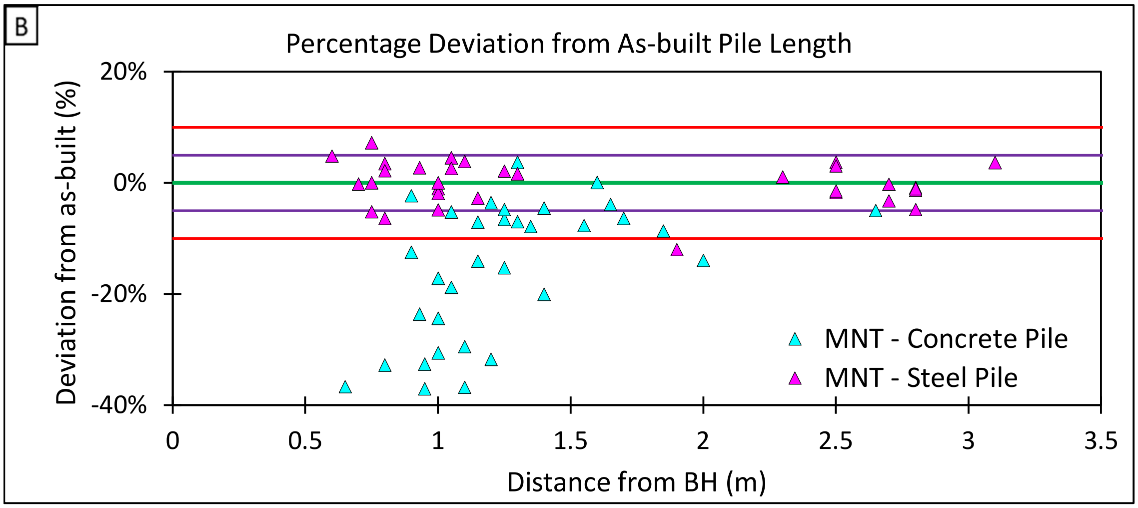


Figure 3.2 Magnetometer Test Result; B. Percentage Deviation from As-built Pile Length

3.3 Pile Length Interpreted by Borehole Radar

More than 10 Borehole Radar tests have been carried out at various locations and a mixed set of results were obtained.

Borehole radar tests were conducted at one of the sites consisting predominantly of Old Alluvium soil and the target piles were concrete pile (700 mm diameter bored pile) and steel pile (300x300x84.5 kg/m). The boreholes were prepared at 1 m away from the pile and as-built information is available. However, no interpretable data were collected. Two independent sub-contractors conducted the tests separately and both yielded inconclusive results (Figure 3.3 A & B).

Another attempt has been made using a lower frequency antenna (100 MHz as compared to 500 MHz used for the initial test) for both concrete pile and steel pile. However, no reflection can be observed on the radargram, refer to Figure 3.3 (C & D). Parallel seismic and magnetometer tests were subsequently carried out for the concrete pile and steel pile respectively, and conclusive results were obtained with the interpreted pile lengths at $\pm$4% from the as-built pile length.

The unsuccessful borehole radar tests at this location is likely due to the ground material being too conductive, masking the signal (if any) from the pile. This could be attributed to the clayey material where a higher conductivity value is expected. From this site, it is observed that the borehole radar test can be very sensitive to the ground condition with limited application in a conductive environment and getting interpretable data in such condition might not be possible.

Six borehole radar tests were conducted at other site and conclusive results were obtained. The site geology consists of Kallang Formation (KF) with underlying Bukit Timah Granite (BTG) residual soil and rock. 500 MHz antenna was used, and the target piles of interest are reinforced concrete piles (205x205 mm) with boreholes at an average distance of 1.37 m away.

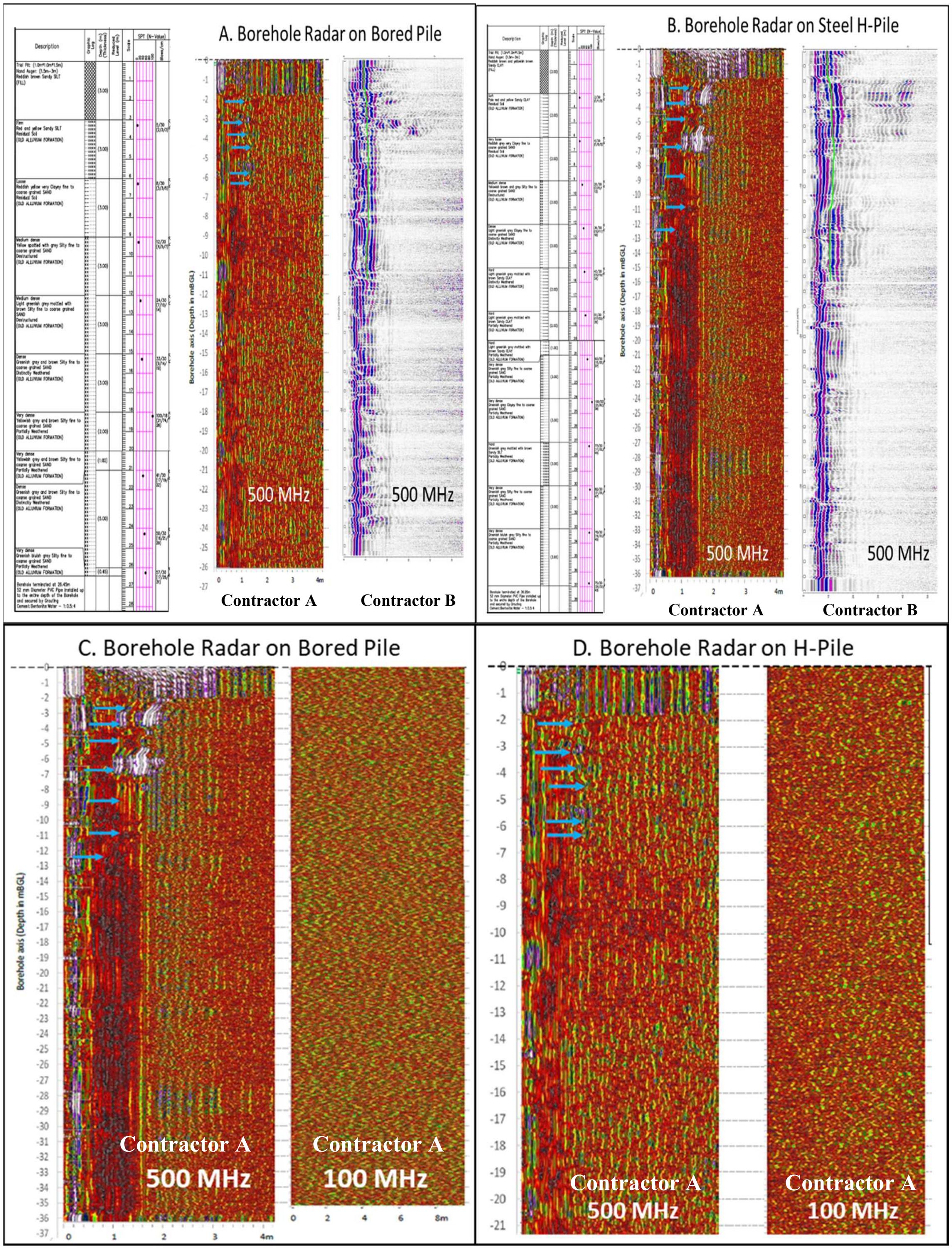


Figure 3.3 Borehole Radar Test Results; A. Borehole Radar on Bored Pile; B. Borehole Radar on Steel Pile
C. Borehole Radar on Bored Pile (500 MHz & 100 MHz); D. Borehole Radar on H-Pile (500 MHz & 100 MHz)

4 CONCLUSION

Determination of pile length under the existing structure is challenging because the investigation method must be non-destructive to maintain the integrity of the structure. There are various methods available for pile length investigation, this paper focused mainly on three geophysical methods that are commonly employed in Singapore which are (i) Parallel Seismic, (ii) Magnetometer and (iii) Borehole Radar. More than 100 test results from past LTA projects where as-built pile length information is available were used in this study and the key findings are summarized as follows:

(i) Borehole should be prepared as close to the pile as possible and tests done up to 3m away from target pile have shown reliable results.

(ii) Parallel seismic tests have shown to be a reliable method when employed on concrete piles with most (90%) of the test results fall within $\pm$10% deviation from as-built pile length.

(iii) Magnetometer tests have shown to be a reliable method when employed on steel piles with most (90%) of the test results fall within $\pm$5% to $\pm$10% deviation from the as-built pile length.

(iv) Borehole radar tests have shown to be highly sensitive to ground conditions. Signal from the pile can be masked when the ground material is too conductive, rendering the test unsuccessful with no interpretable data. Limited tests were carried out in BTG formation showing some reflections from concrete piles.

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