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# Correction of Multi-frequency GPR Wave Velocity with Distorted Hyperbolic Reflections from GPR Surveys of Underground Utilities

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## Abstract

Ground Penetrating Radar (GPR) is a promising non-destructive method for underground utility management and surveying. Estimation of GPR wave velocity and the real part of dielectric permittivity ($\varepsilon'$) play an important role when assessing the condition of buried objects because $\varepsilon'$ is highly affected by moisture and void in materials. However, errors in velocity occur due to the effect of oblique angles between the alignment of pipelines and GPR traverses during common offset survey. In this paper, field experiments on paving blocks and reinforced concrete were conducted in order to investigate errors caused by the effects of oblique angles on GPR wave velocity. GPR traverses were designed to travel along several oblique angles (θ=30°, 45°, 60°¸75°, 90°, 105°, 120°, 135° and 150°) relative to the alignment of a ductile iron (DI) pipe. Antennas with various nominal centre frequencies (IDS 200/600, GSSI 400/900 and Sensor & Software 250 MHz) were applied in order to compare the effects. It was found that wider and flatter hyperbolic reflections are obtained and the estimated GPR wave velocity is higher if the included angle between the alignment of the DI pipe and GPR traverse changes from being perpendicular to oblique. The relative error of velocities estimated at oblique angles when compared to that estimated in perpendicular cases can be as much as 44%. Specific steps were taken to correct the errors. It is believed that this study suggests a method whereby the measurement accuracy of velocity estimation for GPR condition surveys of underground utilities can be increased.

Keywords: GPR; multi-frequency; distorted hyperbola; velocity estimation

# 1. Introduction

## 1.1 GPR wave velocity analysis

Nowadays, Ground Penetrating Radar (GPR) is a well-known non-destructive method for subsurface exploration. Major applications include condition assessment of underground utilities (Costello, Chapman, Rogers, & Metje, 2007; Hao et al., 2012), for example to identify water seepage/leakage and to characterize the dielectric properties/water content of materials ( Lai, Kind, & Wiggenhauser, 2011; Lai, Kou, & Poon, 2012; Lai, Kou, Tsang, & Poon, 2009; Lai, Chang, Sham, & Pang, 2016), for which GPR wave velocity estimation always plays the most important role. The real part of complex dielectric permittivity of a dielectric material, denoted as $\varepsilon'$, primarily determines the GPR wave velocity when the signal travels through such dielectric material, which can be commonly formulated as (Balanis, 2012):

$$v = \frac{c}{\sqrt{\varepsilon'}} \ldots\ldots(1)$$

where $c$ is EM wave travelling velocity in free space and $\varepsilon'$ the real part of complex dielectric permittivity.

In addition to Equation (1), several other major methods can be used for GPR wave velocity estimation, such as depth to known reflector, velocity sounding and hyperbolic fitting. The depth to known reflector method utilizes a target reflector with known depth to calculate the velocity by two-way travel time t, but it is difficult to find such perfect targets on site during underground utility surveys. Also, this method only provides us with a single estimated velocity, which is not accurate enough ("ASTM D6432-11," 2011). For the velocity sounding method in multi-offset configuration, transmitting and receiving antennas are sequentially moved away in opposite directions from the original position and at known distance increments ("ASTM D6432-11," 2011). By measuring the reflection and refraction time, the velocity can be calculated. This method is only applicable for GPRs with separate transmitter and receiver setting antennas but not with common offset configurations. For the hyperbolic fitting method in common offset configuration, velocity is obtained by a curve-fitting process that overlays a typical hyperbolic curve on a user-selected reflection in the radargram ("ASTM D6432-11," 2011; Kohl et al., 2003; Kohl, Krause, Maierhofer, & Wöstmann, 2005). Obviously, the result of hyperbolic fitting can be easily biased as the overlay procedure significantly relies upon the operator's judgement and perception of vague colour contrasts within the radargram. Chen and Cohn (2010 May, 2010 July) have proposed a probabilistic hyperbola mixture model to automatically recognize and select hyperbolas and to perform an efficient interpretation of the GPR radargram on-site. But that model regards the GPR antenna as a point source and neglects the separation between transmitter and receiver, which is not appropriate and leads to inaccurate wave velocity estimation for common-offset setting antennas, especially when antenna separation and target cover depth are of comparable magnitude. A new algorithm for more accurate velocity estimation was proposed by Sham and Lai ( 2016) based on a refined ray path model between antenna and target and trigonometric calculation. It avoids the ambiguous overlay procedure, and considers parameters such as the separation between transmitter and receiver, and depth and radius of cylindrical utility. Further, this algorithm is also implemented by an in-house programme in the LabVIEW environment, which was developed and elaborated in Sham & Lai (2016).

### 1.2 Polarisation effect

The transmitted or received electrical field (E-field) indicates the polarisation of an antenna and usually, a linear object, such as pipeline, acts as a depolarizing feature. If a crossed dipole antenna with linear polarisation is rotated about an axis which is normal to the linear object, a sinusoidal variation of the received signal will be produced (Daniels, 2004; Jol, 2009). A polarisation mismatch can lead to 20 db loss of energy, so the effect is significiant (Annan, 2004).

Commonly in GPR survey, when the antenna perpendicularly traverses across an underground pipeline, the E-field would be parallel to the alignment of the pipeline. The parallelity between the E-field and the alignment of the pipeline helps to form the best-shaped hyperbola that gives the lowest velocity of the GPR wave (Lai, et al., 2016). When an oblique angle exists between the GPR antenna traverse and the alignment of an underground pipeline, the distance from the antenna to the pipeline is reduced from $\sqrt{x^2 + d^2}$ to $\sqrt{x^2 sin^2\theta + d^2}$, as shown in Figure 1. The reduction of flight path causes over-estimation of velocity $v$ and under-estimation of $\varepsilon'$. However, the assumption that GPR traverses are perpendicular to the alignment of the pipeline is not always valid on site. Due to densely arranged underground utilities and their random orientations, it is nearly impossible to guarantee perpendicularity between utilities' alignments and GPR traverses within orthogonal survey grids during underground utility surveys. Further, GPR was previously more often regarded as a propescting tool rather than a piece of survey equipment, which meant that accuracy was not the major concern. As a result, research focused on the relationship between the errors in GPR wave velocity and distorted hyperbolas in radargrams due to oblique angles has been rare (Lai, et al., 2016; Lai et al., 2016; Tanikawa et al., 2013).

Therefore, this paper aims to correct such errors in GPR surveying by firstly investigating the effects of different oblique angles between GPR traverse/antenna polarization and alignment of pipeline on GPR wave velocity, and secondly, by evaluating the velocity variations/errors caused by different oblique angles between GPR traverse and utility alignment. Thirdly, a simple trigonometric function of sinθ is used to correct such errors.

# 2. Methodology and experimental setup

## 2.1 Site description

Field experiments were arranged at the Shek Mun test site (20m*10m) in Hong Kong, which was built in 2016. During the construction, three PVC pipes (diameter 60mm at a cover depth of about 1.0m) and one DI pipe (diameter 200m at a cover depth of about 0.7m) were laid (Figure 2-a) and then fine and dry sand was used to backfill with minimal compaction. Two types of footpath surfacing were used: namely, paving blocks (200*100*60mm thick) and grade 30/20 concrete (100mm thick), which each covered an area measuring 10m*10m. As illustrated in Figure 2, if the alignment of the DI pipe is assumed to be 0°, 13 GPR traverses (red lines in Figure 2-b and Figure 2-c, each traverse is 3m long) were designed to travel across the DI pipe by rotating the traverse over the identical pivot from 0° to 180° at intervals of 15° in order to investigate the effects of oblique angles on velocity estimation. For comparative purposes, GPR experiments were conducted on the surface of the block pavement and reinforced concrete pavement.

## 2.2 Survey Instruments

Common-offset setting antenna, in which the spacing between transmitter and receiver is fixed, were used in this experiment for data acquisition. The schematic diagram in Figure 3 specifically illustrates the ray travel path from transmitter to utility pipe and back to receiver when the antenna is at an oblique and normal position relative to the utility alignment. Three brands of GPR systems (GSSI 400MHz, GSSI 900MHz, IDS 200MHz and IDS 600MHz, Sensor & Software 250MHz) were used for the survey. As each brand of GPR has different antenna frequencies and data acquisition methods, they were all applied to compare the effects and impact upon accuracies caused by the polarisation effect.

## 2.3 Data Processing

Reflexw and an in-house program developed in LabVIEW (Sham & Lai, 2016) were used for data processing. Figure 4 lists the processing steps used in Reflexw (Sandmeier, 1998-2017).

In the in-house program built in the LabVIEW environment, Equation (2) was adopted to calculate GPR wave velocity under the different two modes in LabVIEW, where: '$D_0$' is the depth of the target pipe, 'r' the radius of the target pipe , 'x' the horizontal distance of the antenna from any oblique position to the normal position relative to the target pipe alignment, 'Tx' the two-way travel time of the reflection from the transmitter or receiver to the target at any distance 'x', 'B' is half of the antenna separation distance, and 'θ' is the oblique angle between the GPR traverse and alignment of the pipe as shown in Figure 1.

$$v(x) = \frac{\sqrt{\left[(D_o+r)-\frac{(D_o+r)r}{\sqrt{(D_o+r)^2+(x\sin\theta)^2}}\right]^2+\left[\left(x-\frac{r\times x\sin\theta}{\sqrt{(D_o+r)^2+(x\sin\theta)^2}}\right)-B\right]^2}+\sqrt{\left[(D_o+r)-\frac{(D_o+r)r}{\sqrt{(D_o+r)^2+(x\sin\theta)^2}}\right]^2+\left[\left(x-\frac{r\times x\sin\theta}{\sqrt{(D_o+r)^2+(x\sin\theta)^2}}\right)+B\right]^2}}{t_2} \quad \ldots\ldots(2)$$

The program interface is presented in Figure 5 and some basic procedures are also indicated for velocity analysis as follows: (1) Under the 'Velocity Analysis' tab, input the storage path of the radargram; (2) According to the control unit and antenna used for data acquisition, select the dynamic range and antenna model; (3) Make sure the velocity is analysed with 'Direct Wave' (DW); (4) Select the 'Inflection' point of DW as 'Time Zero' (Lai et al., 2010); (5) Adjust the start and end of DW until the green dot appears correctly at the inflection point of DW in A-scan in (6); (7) Choose the 'Depth known' method to calculate the velocity according to Equation (2); (8) Input the known radius and depth of the DI pipe; (9) Input the oblique angle between the alignment of the object and the GPR traverse, which can be obtained after observing the pipe alignment and GPR traverse direction in the C-scan; (10) Adjust the three lines to identify the hyperbolic reflection (Region of Interest, ROI) until a clear hyperbola is extracted in (11) and then this program will help to calculate the estimated velocity and standard deviation automatically, and display in (12) and (13) respectively.

At the same time, the centre frequency of reflections of the DI pipe under the block pavement and concrete pavement were also obtained for each antenna. The nominal frequency of GPR instruments indicates the centre frequency of the antenna in air (e.g. GSSI 400MHz, GSSI 900MHz and IDS 200MHz). However, this centre frequency is dispersed after signal transmission, reflection or refraction within other materials (Lai, et al., 2011). To investigate the effects of multiple frequencies on GPR wave velocity estimation, it is more reasonable to obtain and compare the centre frequencies of hyperbolic reflections of the DI pipe, rather than those in air. The in-house built program also provides an easy way to acquire such centre frequencies by conducting a 'Wavelet Transform', which re-draws the hyperbolic reflection of the DI pipe in the frequency domain (the '+' cross around the apex of the hyperbola as presented in Figure 6). Figures 7 and 8 show the results and specific values are listed in Table 1.

## 3. Findings and data analysis

Due to the presence of 3 PVC pipes near the DI pipe, there is some obvious scattering and overlapping of hyperbola at the right-hand side of the reflection of the DI pipe. Figure 9 presents a typical radargram hyperbola in which significant scattering and interruption on the right-hand side of the extracted hyperbola can be observed (red rectangular box 1).The right half hyperbola of the target reflection was therefore rejected and disregarded in the ROI and only the left half was used for GPR wave velocity estimation.

Radargrams with hyperbolic reflections of the DI pipe, obtained by 5 antennas at 9 oblique angles ($\theta = 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°, 150°$), are presented in Figures 10 and 11, which show the results from the block pavement and concrete pavement respectively. The target reflections of radargrams at some oblique angles ($\theta = 0°, 15°, 165°, 180°$) cannot be closely matched with a hyperbolic pattern and have the appearance of a layered reflection (as showed in Figure 12 and Figure 13), so those radargrams were excluded from the analysis of effects of oblique angles on GPR wave velocity. Due to the presence of steel bars in the concrete pavement, which resulted in severe absorption and attenuation of the GPR signal, all the reflections of radargrams in Figure 11 were very weak and corresponding hyperbolas were severely distorted when compared with those in Figure 10. However, an obvious trend among the hyperbolas at 9 oblique angles using identical antennas is easily observed; namely, that hyperbolic reflections at oblique angles from 90° to $150°$ or conversely from 90° to $30°$, become flatter and wider. The radargram formed at $\theta = 90°$ possessed the steepest and narrowest hyperbolic reflection. This phenomenon can be better visualized by the extraction of the exact two-way travel time of the target reflection, which is also plotted against the horizontal travel distance of the GPR antenna in Figures 14 and 15. The pair of hyperbolas of oblique angles $\theta = 30°, 150°$ or $\theta = 45°, 135°$ or $\theta = 60°, 120°$ or $\theta = 75°, 105°$ are within close range, while the hyperbolas of oblique angles $\theta = 30°, 150°$ envelop all others. As all GPR traverses ran through the same pivot and the small area of material covering the buried DI pipe is assumed to be homogeneous, then the distortion of hyperbolas at oblique angles relative to the hyperbola at a perpendicular angle must result from the change of included angle between GPR traverse and buried DI pipe alignment, rather than any variation in material properties.

In order to evaluate the importance of correction of errors in GPR wave velocity due to oblique angles, estimated velocities before and after such correction are listed in Tables 2 and 3. Tables 4 and 5 list the valid measurements across hyperbolas in radargrams used in velocity calculation. Velocities, corrected and uncorrected, are plotted as a function of oblique angle $\theta$ as shown in Figures 16 and 17. In terms of the uncorrected velocities in the left-hand diagrams of Figures 16 and 17, the un-fitted curves of velocities versus oblique angles are presented as vertically symmetric 'V'-shapes, with the central lowest point representing velocity at $\theta = 90°$ and the highest points of two sides denoting velocities at $\theta = 30°, 150°$. The vertical symmetry of the un-fitted curve shape denotes that the pair of velocities estimated at oblique angles $\theta = 30°, 150°$ or $\theta = 45°, 135°$ or $\theta = 60°, 120°$ or $\theta = 75°, 105°$ are approximately equal, which is consistent with their similarity of hyperbolic distortion. Obviously, the discrepancy of velocities relative to that estimated at $\theta = 90°$ becomes larger as the GPR traverse rotates away from the perpendicular position relative to DI pipe alignment. However, such discrepancies are significantly reduced after error correction. As presented in the right-hand diagrams of Figures 16 and 17, the previous 'V'-shaped curve is regressed to a nearly horizontal line at the level of velocity estimated at $\theta = 90°$, which implies that the corrected velocities become consistent and stable after the consideration of effects of the oblique angle. In the most extreme case of the block pavement, the discrepancy of uncorrected velocities between the lowest 0.107m/ns at $\theta = 90°$ and the highest 0.154m/ns at $\theta = 150°$ is reduced to that of corrected velocities between 0.107m/ns to 0.112m/ns. The situation is similar in the results for the concrete pavement. Moreover, the standard deviation of estimated velocity is also slightly reduced after such correction, which improves the accuracy and reliability of results.

Percentage error of velocities relative to that at $\theta = 90°$ versus oblique angle $\theta$ is also plotted in Figures 18 and 19. The largest percentage error is reduced from 44% before correction to 6% after correction in block pavement, while from 18% to 2% in concrete pavement. Based on previous analysis, it can be concluded that all velocities, whether estimated in block pavement or in concrete pavement, become fairly constant and stable after correction. This result indicates the importance and significance of considering the effects of oblique angle on GPR wave velocity estimation and of conducting such correction.

Furthermore, the five estimated velocities at $\theta = 90°$ produced by the 5 different antennas are approximately equal in block pavement as presented in Table 2, where the range (1.107-0.099) = 0.008 m/ns, which is 7.9% of the average velocity of 0.102 m/ns, although the centre frequencies of the target pipe reflection with each antenna are not identical (see listed in Table 1). Therefore, the errors caused by antennas with different nominal centre frequencies are not obvious in block pavement. But a similar conclusion does not hold in the case of concrete pavement. In Table 3, velocities estimated at $\theta = 90°$ by the 5 antennas vary with the range (0.115-0.099) = 0.016 m/ns, which is 15.0% of the average velocity of 0.107 m/ns. In comparison with the block pavement surface, where fairly constant wave velocities were estimated with different bandwidths, the estimated velocities for the concrete paved ground surface fluctuated more widely. Generally, the underlying reason for this situation may be attributed to the existence of steel bars in the concrete pavement, which cause significant scattering of GPR waves, especially for higher frequency antennas.

## 4. Discussion

The geometric shape of hyperbolas becomes relatively flatter and wider if the included angle changes from being perpendicular to oblique. The wider hyperbola is obtained because of the increasing length of coverage of the object's footprint. Normally, the hyperbola is a symmetric circular shape if the alignment of a pipe is perpendicular to the GPR traverse. However, the hyperbola reflects as an elliptical shape if an oblique angle exists, so a wider, flatter and asymmetrical hyperbola is obtained. This phenomenon is illustrated in a cross-section of a circular object in Figure 20. When the alignment of a pipeline is perpendicular to the GPR traverse, the offset from the starting point of the effective footprint to the centre position of the object is equal to the offset from the centre position of the object to the ending point of its effective footprint. Hence, a symmetrical and perfect hyperbola is obtained. Nevertheless, the top centre of the object is closer to the starting point of the offset (left-hand side) and is further from the ending point of the offset (right-hand side) when the oblique angle is far away from 90°. Then, an excessive reflection is received when the antenna is moving away from the target object. Therefore, the tail of the hyperbola towards the ending point of offset (right-hand side) is longer than that at the starting point of offset (left-hand side). An asymmetrical and wider hyperbola is therefore obtained in this case. Figure 21 explains the hyperbolic shape based on the concept of radar footprint.

It was mentioned above that clear hyperbolas cannot be extracted from radargrams obtained at oblique angles of 0°, 15°, 135° and 180°. This is because the alignment of the DI pipe is parallel or nearly parallel to the GPR traverse, so there is no offset between them. Only a continuous reflection with similar travel time is observed. If an oblique angle exists, the starting point of the offset of the footprint coverage is not equal to the ending point of the offset, so the hyperbola is deformed into an arc-shape.

## 5. Conclusion

Accurately estimated velocity is absolutely critical in most GPR applications, including condition surveys of underground utilities involving water leaks and void detection. Hyperbolic fitting is one of the most common methods used to estimate GPR wave velocity, but in commercial software the manual dragging exercise used to overlay a hyperbolic curve onto the reflection in a radargram is both coarse and subjective, and the interpretation procedure significantly depends upon operator's perception. Furthermore, the effects of oblique angles between GPR traverses and utility alignments have not received much attention. In this article, the new algorithm proposed by Sham and Lai (Sham & Lai, 2016) was adopted to estimate wave velocity in a field experiment in order to investigate the effects of oblique angles on velocity estimation. Several key factors, such as utility depth, radius and antenna separation, are regarded as known parameters in the adopted algorithm for more accurate velocity estimation. Therefore, errors generated by oblique angles between utility alignment and GPR traverse are identified as being significant and the correction of such errors becomes a very important consideration. Otherwise, without correction the estimated velocity would yield large errors. This paper contributes to the evaluation of these errors as a function of oblique angles, centre frequency of reflected wave and paving materials, and recommends several steps to correct the errors so as to increase the measurement accuracy of GPR wave velocity.

With accurately estimated wave velocity, GPR can be more widely applied in many situations. For example, with commonly used orthogonal GPR survey grids covering a zone of interest with pipes buried underground, GPR wave velocity without correction of oblique angles can at first be calculated (depth and radius of buried pipes can be confirmed by trial pits). By using the C-scan imaging to determine the included angles between GPR traverses and pipe alignments and then correcting errors due to oblique angles, accurate GPR wave velocity and thus reliable distribution of dielectric constants of underground soil can be obtained. This paper therefore provides a more practical and efficient way of accurately measuring dielectric constant. Furthermore, the accurate measurement of dielectric constant allows the determination of a soil moisture distribution map, which is a primary step for water pipe leakage detection using GPR. A large dielectric constant in the survey area indicates a high water content and there is thus a greater possibility of water leakage underground. The reliability of this judgement significantly depends upon the accuracy of estimated GPR wave velocity, which in turn highlights the importance of correcting errors caused by oblique angles between GPR traverses and utility alignments.

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