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Identifying Pipe Leakage with a combination of GPR Wave Velocity Algorithms

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Abstract

Moisture content contained in any dielectric media is the most influential factor reducing Ground Penetrating Radar (GPR) wave velocity, which can be measured by the gradients of diffractive hyperbolas as a result of any round-shaped object, such as water carrying utilities. Such characteristic were then used to estimate location of pipe leak where moisture content is higher in localized area compared to the neighbouring no-leak dry area (Cheung & Lai, 2019). However, depth of utilities is required as a known input in the algorithms based on multiple triangular ray paths using common offset antenna (Sham and Lai, 2016). In this paper, we proposed a combination of velocity algorithm for estimation of velocity, followed by water leak location where wave velocity is reduced compared to non-leak location, without priori information of utility depth. The combination of velocity algorithm was validated firstly using high-frequency 2GHz antenna in air, where wave velocity is equal to speed of light. The second validation is two full-scale studies of water leakage detection by the proposed velocity analytical approach using a 600MHz GPR. Results of both studies substantiate the validity of a combination of few velocity algorithms. It reveals the accurate estimation of pipe seepage and leak location, as a result of 5-10% and 20-30% wave velocity reduction, respectively. The algorithms and validation experiments are believed to pave the way for large-scale applications.

1. Introduction

Hong Kong is one of the most densely populated cities in the world. It has a complex underground utility network to support the daily life of seven million citizens. Since rapid urbanization from earlier 1980s, various types of pressurized pipes were buried including water main, rising main, cooling main and foul drain. The condition of pipe was like most cities, an unknown mystery causing frequent pipe burst. Water leakage accidents were brought to the attention of the public because of its high frequency of appearance in media. According to water supplies department (WSD, 2019), the leakage rate of government mains in underground utilities is approximately 15%. Therefore, a comprehensive leak detection method is essential to locate the leakage from a complex network of underground utilities not only to achieve the sustainable use of water but also prevent the underground hazards like the land subsidence.

Acoustic methods are traditional survey approach applied for locating water leakage in pipe while Leak Noise Correlator (LNC) is an efficient way to determine the leak position (Hunaidi et al, 2004). After the survey by LNC, mechanical leak detector (MLD) can be used to confirm the leak point. The listening stick thus acts as a waveguide to search for the high-pitch leak sound, but this method requires specific experienced personnel to identify the actual leak point. Noting that effectiveness of LNC is restricted by the pipe material like plastic pipe leaks since plastic is a poor conductor of sound wave (Cabrera, 2003). Acoustic methods are always interfered by the environmental and cultural noises which share the same frequency bandwidths.

Apart from mapping the underground utilities, GPR, one of the widely used non-destructive testing (NDT) technologies, is also considered as an effective way to locate leak point of underground utilities with the use of various radar data processing and visualization strategies (Cataldo et al., 2014; Cheung & Lai, 2018; De Coster et al., 2019; Demirci, Yigit, Eskidemir, & Ozdemir, 2012; Hao et al., 2011; Ocaña-Levario, Carreño-Alvarado, Ayala-Cabrera, & Izquierdo, 2018). It is because water content is a dominant factor among nonmetallic materials which attenuates GPR reflected signal amplitude and reduces wave's velocity particularly the high-frequency (Lai et al., 2016). As the electromagnetic waves propagate towards the materials, its velocity and amplitude are a function of relative dielectric properties and electric conductivity (Milsom and Eriksen, 2011).

As water content slows down GPR wave propagation velocity and weakens its amplitude, it can be used as a decisive indicator that depicts abnormal reflection from water content along different GPR survey traverse. Thus, location of water seepage or water leakage by GPR survey can be identified for further open-up action. In this study, a novel velocity estimation combining three velocity estimation equations has been developed by taking complicated triangular ray-paths into account. The method was validated in a control experiment with air as a homogeneous medium of wave velocity and applied in two case studies of water leak detection.

2. Methodology

2.1 Velocity measurement algorithm from diffractive hyperbola in radargram

The diffractive hyperbolas obtained in a radargram is a result of the spread of downward conical footprint (or First Fresnel Zone) of the GPR wave penetrating through a dielectric media and reach a round-shape target with significant dielectric contrast with the host media. When the GPR dipoles/E-field direction is parallel to the alignment of the utility, or the antenna traverse is perpendicular to the alignment of utility in most ordinary common offset configuration, the utility will appear as a diffractive hyperbola described by the equations in later section of this paper. Gradient of the hyperbola carries the important information of wave velocity that relates spatial and lateral position (x) to travel time (t) as shown in figure 1, modeling the hyperbolic reflections accurately is essential in velocity analysis. Most importantly, it indicates material wetness directly affiliated to pipe leak.

For common offset configuration of velocity estimation,

(a) Velocity measurement by stationary single point

The most simplified equation considers two-way travel time for estimating the GPR wave velocity. It is only applicable when the depth of the object point or any flat continuous surface is known.

$$v = \frac{2D_0}{t}$$

(1)

where:

t = two-way travel time of the signal reflected from the object,

D_0 = depth of the reflected object.

(b) Velocity algorithm by single trilaterated method with a round-shaped reflector as point-source target (ASTM D6432-2011)

This equation is being widely used in commercial software for hyperbolic fitting, based on an assumption that pair of transmitting and receiving antennae, and the target utility are all point sources. It follows that both antenna separation and size of objects are not taken into account.

$$v(x_i) = \left(\frac{2}{t_0}\right)\left[\frac{x_i}{\sqrt{\left(\frac{t_i}{t_0}\right)^2 - 1}}\right]$$

(2)

where:

x_i = horizontal distance between the antenna at an oblique position 'i' to the apex of hyperbola if the GPR traverse is perpendicular to the alignment of the studied linear object,

t_i = two-way travel time of a reflection from an interface at antenna position 'i',

t_0 = two-way travel time of a reflection from an interface when the antenna is directly on top of the utility.

(c) Velocity algorithm by multi-trilaterated ray-path method (only target as point source)

Point-source assumption in method (b) is for the purpose of simplicity. In reality, actual ray-path is more complicated and requires more understanding of the actual geometry of the antennae (i.e. separation of transmitter and receiver), as well as the second triangle (on-plane) existed between the GPR traverse and utility alignment creating a non-right angle on plan. Therefore, by taking antenna separation '2B' and oblique angle θ between traverse and utility alignment into consideration, equation (3) is developed.

$$v(x_i) = \sqrt{\frac{2(x_i \sin\theta)^2\, t_i \pm 2x_i \sin\theta\, ((x_i \sin\theta)^2\, t_i^2 - 4B^2 t_i^2 + 4B^2 t_0^2)^{0.5}}{t_i^3 - t_0^2 t_i}}$$

(3)

where:

x_i = horizontal distance between the antenna at an oblique position 'i' to the apex of hyperbola,

θ = oblique angle between the pipe alignment and GPR traverse,

B = half of the antenna separation distance,

t_i = two-way travel time when GPR is oblique to object,

t_0 = two-way travel time when GPR is normal to object.

(d) Velocity algorithm by multi-trilaterated ray-path method and estimated cover depth D_0 and radius (Sham and Lai, 2016)

For even more accurate measurement of velocity, known depth (D_0) and radius (r) of the object are further considered according to Sham & Lai, (2016); Xie et al. (2018), in addition to the factor of antenna separation and angle in equation (3) as shown in the programming platform in figure 2 and figure 3.

$$\mathrm{v}(\mathrm{x_i}) = \frac{\sqrt{[(D_0+r) - \frac{(D_0+r)r}{\sqrt{(D_0+r)^2+(x_i \sin\theta)^2}}]^2 + [\left(x_i - \frac{r(x_i \sin\theta)}{\sqrt{(D_0+r)^2+(x_i \sin\theta)^2}}\right) - B]^2} + \sqrt{[(D_0+r) - \frac{(D_0+r)r}{\sqrt{(D_0+r)^2+(x_i \sin\theta)^2}}]^2 + [\left(x - \frac{r(x_i \sin\theta)}{\sqrt{(D_0+r)^2+(x_i \sin\theta)^2}}\right) + B]^2}}{t_{x_i}}$$

(4)

where:

x_i = horizontal distance between the antenna at an oblique position 'i' to the apex of hyperbola

θ = oblique angle between the pipe alignment and GPR traverse,

D_0 = estimated depth of the object from equation (1) & (3),

r = radius of object

B = half of the antenna separation distance,

t_{x_i} = two-way travel time when GPR is oblique to object,

t_0 = two-way travel time when GPR is normal to object.

Table 1 summarizes the parameters for velocity measurement method which is discussed in this section. Whilst object size (radius 'r') can be obtained in record drawings, antenna separation (two times 'B') is known in manufacturer's menu and angle ('ɵ') can be measured after observing the grid direction and utility alignment in 3D imaging, depth ('D_0') is not available most of the time. It is also a paradox for estimating velocity through known depth, while depth of the utility is, in itself, the purpose of the survey. The combination of algorithms solves this problem by combining the above few equations so that the both velocity and depth can be estimated. Note that the outlier of velocity data are all filtered by setting a standard deviation limit to 0.01m/ns (10% of normal velocity in soil, i.e. 0.1m/ns) and velocity data points larger than 0.2998 m/ns (speed of light) are treated as invalid outliner. The reason of doing this is to eliminate the velocity outlier calculated due to the relatively unreasonable small difference of time of flight between the apex and location close to the apex of the hyperbola. In other words, the setting of the limit was made purposely for calculating velocity profiles on the locations much away from the apex of the hyperbola, or the diffractive and relatively linear part of the hyperbola. Note also that the process of elimination was done separately on the left and the right side of the hyperbola. Therefore if velocity values between the left and right side of the hyperbola are different, the overall reported standard deviation will exceed the 0.01 m/ns threshold.

As shown in figure 4, the proposed combination of velocity measurement method is a new approach for estimating GPR wave velocity by substituting mean of $\mathrm{v}(x_i)$ in equation (3) into V in equation (1) to estimate D_0 then substitute the estimated D_0 in equation (4) to re-calculate $\mathrm{v}(x_i)$ and D_0. Not also in this paper, the effect of oblique angle (sin θ) does not affect velocity estimation in equation (3) and (4) because the GPR traverse is always perpendicular to the alignment of the buried linear object, which makes sin (90°) is always equal to 1.

2.2 Velocity validation in air

Validation test in a known environment and controllable manner is crucial for any new proposed algorithm. As GPR wave travels in speed of light (0.2998m/ns) in homogeneous medium - air, the air-steel verification test can evaluate the constituency of the proposed velocity analytical method combining equation (1), (3), (4) by comparing the percentage error of resulted velocity with the velocity from equation (3) standalone only and equation (4) using model answer of known object depth. As shown in figure 5, a 2GHz antenna was used for the calibration of wave velocity in air as the media for radar signal transmission. A wooden board (for running GPR traverse) and a Y25 steel bar were placed inside a rack so that the distance between the GPR antenna and the Y25 steel bar could be adjusted (i.e. 300mm and 400mm). The GPR antenna was moved perpendicularly to the Y25 steel bar and the radargram of the traverse was used for velocity analysis (Sham and Lai, 2016). The analysis was done by measuring the velocity of the reflected wave at different depths with a 2GHz antenna using the proposed GPR wave velocity analytical method.

As shown in figure 6, the calculated discrete velocity using the proposed combination of velocity algorithms involving equation (1), (3), (4) are more consistent than those obtained from only equation (3). It is evident in Table 2, that the velocity from equation (1), (3), (4) are more concentrated in the range of 0.29 - 0.3m/ns which is an ideal wave velocity in the air with reference to the constant line of the speed of light.

In 300mm target depth, result from equation (3) underestimates the GPR wave velocity by 10% compared to the speed of light, while result from the combination of velocity algorithms yields only 1% less than the speed of light, and equation (4) with model answer of object depth measured by tape as input can give a zero-error result. In 400mm target depth, the estimated velocity from equation (3) is still underestimated by 9%, but the combination of velocity algorithms can give a zero-error result, and the equation (4) underestimates the velocity by 1%.

Concerning the standard deviation of the velocity data points, in 300mm depth, the proposed velocity algorithm with 0.0009m/ns is smaller than 0.0500m/ns from the equation (3) but larger than 0.0007m/ns from equation (4). In 400mm depth, the proposed velocity analytical method with 0.0003m/ns is smaller than both 0.0481m/ns from equation (3) and 0.0011m/ns from equation (4). Such small errors suggest that the velocity algorithms give highly accurate estimation of GPR wave velocity in the validation test.

2.3 Validation in two field experiments

Before using the datasets for further velocity analysis as case studies. All datasets should be post-processed to enhance the overall image quality of the radargram.After standard data processing according to LSGI (2019), the radargrams are processed by the new velocity algorithm programmed in the inhouse LabVIEW program shown in figure 2 (Sham & Lai, 2016). Then, the 2D velocity profiles were generated afterwards after applying a moving average filter.

Case study 1 - controlled field experiment in Shek Mun, Hong Kong

The first case study makes use of datasets collected in a controlled-water leakage experiment. Cheung & Lai (2019) makes use of only equation (4) to validate the proposed velocity algorithm. This paper makes use of the same set of data but adopt equation (1), (3) and (4) for velocity estimation. The experiment setup simulates a controllable progression pattern of water-leak scenario from smaller seepage to leak given that the location of the pre-defined drill hole and displaced joint were known, and the same datasets surveyed by IDS RIS MF HiMod 600MHz central frequency GPR with profile spacing of 0.5 m , were used to check whether the same leak point can be pinpointed by the combination of velocity algorithms and its consistency of measurement.

The field experiment was set up in On Muk Street, Shek Mun, Hong Kong where the site is divided into two parts: reinforced concrete slab and block paver constructed as shown in figure 7 according to construction guideline of pedestrian walkways from Highways department, HKSAR Government (Highways Standard Drawing H1102B, 2014; Highways Standard Drawing H1103F, 2014; Highways Standard Drawing H6168, 2014). A 200mm ductile iron pipe was buried with

0.59m depth in a relatively flat ground without change of depth. (Lai et al.,2018; Cheung & Lai, 2019)

According to Figure 7, a total of four leak point was predefined on site. When water being injected into the pipe, water leak from these points and spread out to the surrounding soil. Since the depth of the pipe (D_0) in this case study was measured from on-site measurement. The following velocity analysis implemented equation (4) which required a given D_0 as input (Cheung & Lai, 2019). Figure 8 shows the level of velocity drop across the two paving materials which is concrete paving and block paving. In concrete paving, the velocity drops are 14% and 22% in leak point X2 and X14, respectively. While in block paving, the velocity drops are 5% and 2% in leak point X26 and X37, respectively.

By implementing the proposed combination of velocity algorithms which combines equation (1), (3), (4), D_0 is not required for the velocity analysis. The results show a 9% of velocity drop and 4% of velocity increase in leak point X2 and X14. While for block paving, 7% of velocity increase in leak point X26 and velocity drop of 6% in leak point X37 as shown in figure 8. In Figure 9, it is evident that the range of standard deviation (i.e. the error) of each velocity measurement after leak is higher than that before the leak. It is because of the increasingly heterogenous environment causing more scattering and absorption of GPR wave, hence distorting the original intact shape of hyperbolic tails in the case before leak. In addition, there is no significant difference between the use of the two algorithms, i.e. equation 3 alone and combined equation 1, 3 and 4.

Case study 2: real case in Island Road, Hong Kong

The site is located in Island Road, Deep Water Bay, Hong Kong (Figure 10), where a 300m long ductile iron and pressurized rising main with 450mm diameter was reported that the pressure of upstream pump station dropped from 3 bars to 1.5 bars. The drop of pressure indicated that there is potential leak point along the pipe. All acoustic methods including leak noise correlator and listening stick had been used but were in vain. In this study, IDS RIS MF HiMod 600MHz central frequency GPR with profile spacing of 1m and GPR velocity analysis method was used to detect the water leakage point of raising main in Island Road, after both secondly 2D radargram velocity analysis and firstly 3D GPR time slice visualization and finally the leak point was successfully found and confirmed by open up.

Firstly, 3D time slice imaging was conducted according to the 3D process flow in Luo et al. (2019) and shown in Figure 11. A continuous reflection of the rising main had been observed from the top view of the 3D time slice, but it is obvious that there is weaker amplitude at point A (811562m Northing in Hong Kong 1980 coordinates system) as reflected energy is mostly absorbed by the water content surrounded the leak point. Secondly, based on the same set of data processed with time slice, the combination of velocity algorithms was used to give velocity profile across the hilly terrain.

The result shows that GPR wave velocity dropped significantly around the actual leak point (818562m northing) confirmed by open-up trial pit, as shown in figure 12. The profile of velocity forms a cave shape. By comparing lateral wave velocity from individual radargram with the mean velocity throughout the whole GPR traverse, obvious percentage difference of wave velocity was observed. The high percentage of velocity drop compared to the mean velocity, indicates that a significant accumulation of water slows down the wave velocity up to 30% as shown in top of figure 12. It is an important indicator which shows the water content around the leak point slows down the GPR wave velocity and explicitly suggests the location of leak point.

3 Discussion

3.1 30% velocity changes as leak indicator

By measuring the velocity of the host material velocity analysis of host material (i.e. soil) on top of the target object (i.e. pipe), the overall velocity distribution should be a constant with relatively stable velocity profile in a no-leak pipeline. As reduction of velocity is a common indicator to prove the increase of water content in the soil as the GPR wave propagation was retarded, leak points can be identified by pinpointing the area that shows around 30% of velocity drop as shown in figure 12 in case study 2. The only unresolved matter is how to measure it correctly. This work provides a reliable algorithms and data collection methods in this regard.

3.2 Constituency of the combination of velocity algorithms

The study reveals the consistency of the proposed velocity algorithm in identifying water leakage by GPR. In case study 2, it is worthwhile to note the standard deviation of velocity data points along the pipe drops from 0.013m/ns to 0.002m/ns which is 88% less than equation (3) standalone after implementing the proposed combination of velocity algorithms involving equation (1), (3) and (4) as mentioned. The smaller standard deviation of the proposed method implies that the mathematical model for estimating the velocity is more consistent and it can result in a more consistent velocity profile.

4 Limitations

There are still three limitations in the analysis for pinpointing water leak due to the selected region of interest (ROI) and assumption of constant wave velocity.

4.1 Scattering effect on wave velocity estimation

From case study 1, the error bars show that the overall standard deviation of wave velocity after water leak is much larger than that before water leak. This can be explained by scattering effect of various grain sizes in soil of inhomogeneity. Since distribution of water content further intensifies the original inhomogeneity of the host environment resulting in change of the triangular ray-paths. Thus, the resulted hyperbolas are further distorted which affected the overall standard deviation of the estimated velocity in the measurement.

4.2 Incomplete hyperbolas within region of interest (ROI)

The proposed algorithm relies on the selection of the region of interest (ROI) containing the full targets' hyperbolic reflections. Any distortion of the hyperbola caused by deviation of ray-paths results in a significant standard deviation of the estimated velocity. In some cases, even only one side of the symmetric hyperbola is available. As a result, a single side of hyperbola does not work as the algorithm requires a good definition of the location of hyperbolic apex. As the peak time is designed to be automatically picked by comparing the two-way travel time of each independent data points on the two sides of the hyperbola, single-sided hyperbola requires manual picking of hyperbolic apex. Such pick can be an arbitrary and operator-dependent process.

In reality, the scattering effect and attenuations of the GPR signal will distort the target hyperbola. Those noises and disturbances can be caused by:

i) The neighboring underground utilities including those metallic and non-metallic pipes, similar to the limitation 4.1

ii) Individual scatterers such as gravels and pebbles whose sizes are comparable to the GPR wavelength

iii) Attenuation of the radar pulse reducing signal to noise ratio for recognition of the hyperbolas

4.3 Assumption of constant wave velocity

All velocity algorithms mentioned assume constant GPR wave velocity within the medium between the GPR antenna and the target objects. In reality, the engineering structure of the ground is always in different layers and are likely subject to uneven compaction of the back-fill materials affecting wave velocity. Therefore, the estimated GPR wave velocity is subject to variation between concrete, block paver and soil layers at different depths, but it is assumed homogeneous in the algorithms.

5 Conclusion

This paper provides solutions in two aspects. Firstly, it has been well-known that GPR wave velocity is dependent on material properties like water content. This paper modifies the algorithm by combining the computation of diffractive hyperbolas. Advantage is on one hand, taking into account the complicated trilaterated ray-path due to antenna separation, object size, angles between antenna B-field polarization and object alignment. On the other hand, object’s cover depth is no longer required as an input parameter. Secondly, such algorithm can be used to locate water leak point with high level of confidence. It is believed that these two aspects will benefit the scientific and engineering committees, that GPR is not only an object mapping tool, but also an useful diagnostic tool of city underground.

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