This is the Pre-Published Version.

Field Validation of Water-pipe Leak by Spatial and Time-lapsed Measurement of GPR Wave Velocity

Bella Wei-Yat Cheung and Wallace Wai-Lok Lai*

Department of Land Surveying and Geo-Informatics,
The Hong Kong Polytechnic University, Hong Kong
Corresponding author: wllai@polyu.edu.hk*

ABSTRACT

Invisible water leak detection in water pipe is a nationwide issue because of pipe aging and intrusion by aggressive agent. Nondestructive geophysical methods for identifying leak points are always a tool of highest priority. Such task is usually conducted by acoustic method. But in this paper, GPR is attempted as an alternative or perhaps a replacement in some occasions because of its high sensitivity to the presence of water in soil. So it is potentially applicable to pinpoint leak in buried water pipes with proper methodology.. This paper presents a methodology for such purpose by a field-scale GPR experiment. Four water leak points of a buried ductile iron water mains were pre-designed in a full-scale mockup (20m long x 10m wide) paved half by reinforced concrete and half by paving blocks. Four GPRs with five GPR nominal frequencies 200MHz, 250MHz and 400MHz, 600MHz and 900MHz were tested and compared. Then, based on a modified algorithm of common offset GPR antennae, this paper measures changes of wave velocity and wave reverberation which contribute to upward and downward leak, respectively. Leaks were found to be most sensitive in 600MHz GPR data. This work is also concluded by suggesting two potential applications for detecting multiple leaks for old pipes that are leaking, and new pipes' testing and commissioning before and after pressurized test. The methodology and validated results offer another possibility of studying and quantifying extent of pipe leak using GPR, apart from the traditional acoustic method which are highly affected by environmental noise.

1. Introduction

1.1 Background of water leak detection

With the expeditious developments and rapid growing populations especially in the cities and metropolises, the invisible underground is not only congested with public utilities but also subsurface facilities such as transportation networks, storage (eg. waste, food, water, oil, industrial matters), industry (energy generation, water treatment) and even public living element (eg. retail complexes, parking spaces, civil defense structures) (Bobylev, 2009; Broere, 2016; Wallace & Ng, 2016). In most of the Asia cities like Japan, Taiwan and Hong Kong, the underground worlds are very complex and in disorder. Taking Hong Kong, one of the most densely populated metropolises among the globe, as an example, it possesses a remarkably 'spaghetti-like' unseen underground utilities network with more than 4,000 kilometers of stormwater drains and sewers and around 8,000 kilometers of water mains were embedded underneath Hong Kong (Drainage Services Department, 2016; Water Supplies Department, 2017). The aged pipe networks and disrupted

This is the peer reviewed version of the following article: Cheung, B. W. Y., & Lai, W. W. L. (2019). Field validation of water‐pipe leakage detection through spatial and time-lapse analysis of GPR wave velocity. Near Surface Geophysics, 17(3-GPR in Civil and Environmental Engineering: Recent Methodological Advances), 231-246, which has been published in final form at https://doi.org/10.1002/nsg.12041. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions. This article may not be enhanced, enriched or otherwise transformed into a derivative work, without express permission from Wiley or by statutory rights under applicable legislation. Copyright notices must not be removed, obscured or modified. The article must be linked to Wiley's version of record on Wiley Online Library and any embedding, framing or otherwise making available the article or pages thereof by third parties from platforms, services and websites other than Wiley Online Library must be prohibited.

underground environment result in significant increase of water bursts and seepages, such that up to 25% of fresh water loss every year (Yue & Tang, 2011), as well as the undiscovered subsurface washouts. Water leakage/seepage detection diagnosis is crucial in minimizing water loss in the pipes in the invisible underground and reducing disturbance to road users and residents in the very limited living environment in most Asia cities. Leak Noise Correlator (LNC) and pipe pigging is a widely-adopted technology to identify leak points detect water leakage by calculating the time delay variances and predicting the wave speed in the pressurized water pipe network (Hao et al., 2012). LNC requires recording of leak noise under a circumstance that sound/vibrational interruption in the water distribution system during the detection procession must be minimal. However, LNC method, like all nondestructive testing method, is limited due to a number of factors like its contact with the pipe, inadequate pressure, variation of pipe materials and pipe size (Gao et al., 2005; Hao et al., 2012) . In some cases, like the early-stage water leaks in gravity pipes, pressure-lost leaking pipes or large-diameter trunk pipes, where wave transmission is considered as unfavorable, the location of leak points could not be determined (Gao et al., 2005; Hao et al., 2012; Liu & Kleiner, 2013). Ground penetrating radar (GPR), is not limited by the above disadvantages because its wide bandwidth of high frequency electromagnetic spectra, latest antenna shielding design and its ground-couple nature makes insensible to environmental noise and other factors like weather.

1.2 GPR velocity analysis in Pipe Leak Characterization

Ground penetrating radar is one of the best indicators in measuring distribution of water content. It is proven to be able to detect early-stage water leaks in different pipe materials, not limited to PVC pipes and metallic pipes via different lab-scale experiments (Ayala-Cabrera et al., 2011; Bimpas et al., 2010; Cataldo et al., 2014; Crocco et al., 2009; Demirci et al., 2012; Glaser et al., 2012; Goulet et al., 2013; Lai et al., 2016; Lai et al., 2017b; Ocaña-Levario et al., 2018). GPR is a widely applied non-destructive method for near-surface detection as well as buried utilities mapping (Metwaly, 2015; Prego et al., 2017; Sagnard et al., 2016). The reasons for GPR being used as pipe water leaks method is based on mechanism of dielectric polarization, where water molecules in free form contained in material is easily polarized by incident GPR wave to reduce wave travel speed. This mechanism is used to study water leak in this paper. GPR also allows hazards like subsurface voids and washout to be efficiently assessed in high resolution (Cassidy et al., 2011; Lai et al., 2017a; Nobes, 2017) because physical contact between the sensors and objects is not required when compared to acoustic methods such as leak noise correlation or pipe cable location(Liu et al., 2013). With a wide frequency range, various GPR antennae allow applications on variable physical properties or structures of underground environment, and apply in different paving materials including asphalt, concrete paving and block paving in road networks in most densely populated cities (Cassidy et al., 2011; Fernandes et al., 2017; Loizos & Plati, 2007; Metwaly, 2015; Shangguan et al., 2014; Tosti et al., 2016; Tosti et al., 2018; Yehia et al., 2014).

The mapping of water leak's perturbation through slice scan in horizontal plan is a validated method to trace the leak locations of water pipes in materials like sand and concrete (Lai et al., 2016; Lai et al., 2017b), as a result of wave attenuation by free water content. However, the complex subsurface environment is usually closely packed with all kinds of utilities. which makes it less favorable for tracing the leakage/seepage of water pipes. The velocity analysis method attempted in this paper is arguably a better diagnostic method because it requires a comparison of wave velocities before and after water leak In GPR wave propagation, different kinds of velocity estimation approach can be applied, including depth to known reflector, velocity sounding, and hyperbolic geometry methods, or assumption of dielectric constant (ASTM D6432-11, 2011) to estimate the GPR wave velocity. The hyperbola fitting method is one of the methods that could be used to estimate the GPR wave velocity in material in common offset transmitter to receiver's configuration, which is written as in ASTM D6432-11 (2011):

$$D = \frac{x}{\sqrt{\left(\frac{t_x}{t_0}\right)^2 - 1}} \quad ; \quad v = \left(\frac{2}{t_0}\right)\left[\frac{x}{\sqrt{\left(\frac{t_x}{t_0}\right)^2 - 1}}\right] \qquad (1)$$

where t_x is the two-way travel time of the transmitting EM wave to the target and reflecting back to the antenna at Position 1 as shown in **Error! Reference source not found.**; t_0 is the two-way travel time of the transmitting EM wave to the target and reflecting back to the antenna at position 2 as shown Figure 1; x is the distance between the two positions along ground surface; v is the wave velocity in materials with unit 'm/ns'.

However, four geometric effects: (1) pipe size, (2) depth of object, (3) antenna separation and (4) included angle between the traverse and the object alignment are not considered in equation [1] and Figure 1. After taking these four parameters into account, raypath in Figure 2 is re-constructed and mathematically represented in equation [2] (Sham et al., 2016b; Xie et al., 2018).

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

where B is half of the separation of the transmitter and receiver in a shield antenna; 'D_o' is the known depth of the object, 'r' is the radius of the embedded pipe, 't_x' is the two-way travel time of the transmitting EM wave to the target and reflecting back to the antenna at any distance of 'x'. θ is the included angle between the GPR traverse and pipe alignment where two schematic diagrams are illustrated in Figure 3 and Figure 4. A non-right angle results in a distorted polarization effect in GPR radargram and gives a erroneous measurement of velocty. Details of the error is reported in Xie et al. (2018). In this paper, equation (2) was used in estimating wave velocity in a full-scale field experiment for a well-controlled water-leak scenario where four leak points made of poor joint connections were made in a water main. The pipe is covered by two commonly used road pavement materials: paving block and reinforced concrete. In particular, antennae of 5 GPR frequencies (200MHz, 250MHz, 400MHz, 600MHz and 900MHz) were attempted to study the sensitivity of detecting leak with different GPR antenna frequencies.

2. Methodology: Design of the test site and experimental setup

2.1 Details of the Test Site

A full-scale water leak scenario of buried water main was experimented in a test site as shown in Figure 5, which is a setup at the Road lab of Department of Civil Engineering, The Hong Kong Polytechnic University. It is located in Shek Mun, the New Territories, Hong Kong. The dimension of the test site as shown in Figure 6 is 20m (Length) × 10m (Width). It is overlaid with two different paving materials, in which a 200mm diameter, 0.59m deep ductile iron (D.I.) pipe (external diameter 220mm) was embedded. The construction of the site followed the local specifications and drawings by the Highways Department, HKSAR Government. The construction details could be referred to H1102B (Highways Standard Drawing H1102B, 2014), H1103F(Highways Standard Drawing H1103F, 2014) and H6168, H6169, H6170 (Highways Standard Drawing H6168 H6169 H6170, 2014). Considering the common pipe defects that could be found in the water-carrying underground network or pressurized of gravity pipes including raising mains, fresh water supplies, storm water drains and sewers, displaced joints are likely to be a symbol of pipe leakage, that water leaks out from a defected pipe in service continuously. There were four pre-meditated leak points (made of pipe joints) in the D.I. pipe as shown in Figure 7. The as-built locations of leak points (i.e. the joint connections) were verified and confirmed after reviewing the chainage of those joints captured by in-pipe CCTV inspection. A bundle of PVC pipes is placed next to the D.I. pipe to deliberately observe interference on the D.I. pipe reflections. Interference was later found to be quite minimal compared to the strong reflection by D.I's metal pipe. The test site is originally used to study six buried voids reported in Lai et al. (2018). As the voids are not close to the pipe, their effects are negligible in this paper.

- *Water Leaks in Pipe*

Under the controlled environment, pipe leak and seepage scenario were created by injecting total amount of 7.26 m^3 fresh water with a constant flow rate of 0.0356 (m^3/min) lasted for 204 minutes from the water hose installed at S01 which is the upstream of the pipe (Figure 8). The GPR surveys were started before the start of water injection ($t = 0$) and during the water injection ($t = 178$ mins to $t = 204$ mins), after 178 mins of water injection. In the beginning, it was assumed and later verified that the water leaked out at the leak points C1, C2, P1 and P2 which are the joint connections of the water pipe.

- *GPR Data Collection*

GPR survey was performed in a 3m x 19m survey area where the grid is 1.5m offset from the metallic water main along the 19-m long pipe section over the two paving materials. The grid was established in X and Y direction and in zig-zag mode as shown in Figure 8. The grids in x-direction were perpendicular to the water main with spacing of 0.5 m which were indicated by the blue and yellow lines (Figure 7) and therefore the included angle in equation 2 is always a right angle; the y-direction was placed along the metallic water main which was indicated by the red line in (Figure 7). It allows us to obtain the best velocity measurement where error of GPR wave propagation velocity could be minimized when the GPR traverses were perpendicular to the pipe alignment (Xie et al., 2018). The GPR survey was carried out in sequence with a Zigzag path in single-tracing to minimize the survey time of each antenna and to shorten the lag time between the data collection during the non-stop and constant water injection, as shown in Figure 8. The GPR surveys were done in two stages which were carried out *before* and *after* water injection. The sequence of the GPR survey was GSSI 400 MHz, IDS 200/600MHz, Sensor and Software 250MHz, then GSSI 900MHz.

3. Data Processing

The collected GPR data was processed by two software which are 2D signal processing by ReflexW, and velocity analysis by an in-house GPR wave velocity analysis program in LabVIEW (Sham & Lai, 2016a; Xie et al., 2018). The B-scans undergo a basic signal processing including dewow, direct current shift, time zero correction, background removal and energy decay to adjust the drift of waveform and stand out reflected signal from the water main. The bandpass filter is also applied to the data of reinforced paving to eliminate the reverberated signal and noise.

Equation 2 was programmed in LabVIEW to iterate the computation along the traverse, in which the interface is depicted in Figure 9. Distribution of discrete velocities at each point oblique to the embedded object was computed. As shown in Figure 10, the program interface displays a selected radargram (B-scan) for hyperbola selection. Display of clear hyperbola in the distance-time curve is generated by the selected hyperbolic reflection while the corresponding discrete velocities at each point of the hyperbolic reflection is shown in the below plot within the same program. The specific parameter like the antenna's center frequency and the angle of the pipe alignment to the GPR traverse are required (Figure 9). Outlier data are rejected if a standard deviation of velocity 0.01 m/ns across the hyperbolic tail is exceeded.

4. Results

4.1 Observation and Interpretation of Radargrams

Amongst all radargrams in the 39 traverses, four representative radargrams X2, X14, X26 and X37 were selected because they coincide the locations of the leak points C1, C2, P1, and P2, where C1 is the closest and P2 is the farthest from the upstream water injection point. The D.I. pipe reflections are always in the middle of the radargrams for all frequencies. Radargrams before and after the water injection in these four locations are shown in Figure 10 in order to observe the effects of wetness of underground materials and pipe's signal reflection on the signals captured at the water leak locations. By comparing the 'before' and 'after' radargrams in Figure 10, three abnormal features and phenomena could be identified to explain the GPR responses at the leak points. *First,* the red line compares the first arrival time of hyperbolic peak (i.e. the position before the water leaks out from the leak points) with that of the hyperbolic peak after water injection. The hyperbolic reflection drops significantly in upstream leak point C1 indicating that the GPR wave travel time to the D.I. water main was comparatively longer after the water injection. *Second,* the increase of water content in soil prolongs and diffracts the GPR ray-path in a wetter medium, and results of which (i.e. velocity) are measured through the methodology suggested in previous sections, and presented in following sections.

4.2 Velocity Analysis in various GPR frequencies

- *Comparison between equation 1 (ASTM D6432-11, 2011) and equation 2 (Sham et al., 2016a)*

The velocity profiles of the pipe with concrete pavement and brick pavement, in a total length of 19m were plotted by using the distinct EM wave velocities collected by the common offset GPR antenna. Figure 11 shows the comparison of calculated velocities retrieved by the traditional hyperbolic geometry method (equation 1) and the modified velocity analysis program (equation 2) using the GPR data collected before the water injection. The result indicates that the velocity estimation by hyperbolic geometry method (equation 1) is less reliable as the standard deviation of each estimated velocity is large as evidenced by the error bars in Figure 11. On the contrary, equation 2 embedded in the velocity analysis program provides a more accurate and consistent velocity estimation which is a prerequisite for measuring minor change of velocities after water leak.

- *Measurement of lateral velocity variation*

The velocity analysis comprises of two parts: Firstly, the distinct velocity changes at the traverse perpendicular to the leak points of the pipe was compared. Secondly, velocity was picked from the hyperbola reflection from traverse X1 to X39. Increase of water content at leak points contributes to the lateral reduction in GPR wave propagation velocity in general. Drop of velocity exists in all hyperbolic reflections amongst all frequencies at the leak points. This magnitude of velocity drop is reported in Table 1 with the percentage difference between the 'before' and the 'after' cases calculated by equation 2. It is observed that the most significant drop of velocity was found over the leak points under concrete pavement along the two upstream leak point C1 (traverse X2) and leak point C2 (X14) as shown in Table 1. When the hyperbolas before and after water leak show no change as shown in traverse X32 in Figure 12, it indicates the 'no-leak' case.

The velocity analysis results acquired from before and after the water leak using 200MHz, 250MHz, 400MHz, 600MHz and 900 MHz is shown in Figure 13a-e. The velocity lines in yellow indicates the GPR wave velocity after water injection; while the grey line represents the velocity before the water leaks (dry state). The velocity is indicated by the major axis and the percentage drop of velocity is shown in the minor axis. By relating the velocity to chainage of the traverse, the lateral reduction of velocity after water injection is clearly visible at the leak points and in all GPR with different frequencies. From the result of the experiment, the velocity picked from the traverse closest to the leak points is relatively lower than that of other traverses within the same axis. This fact is realized by the percentage drop of velocity (the blue bars shown in secondary axis to the right). It could be explained by the increase of dielectric constant with the increased water content in soil compared to the dry area, which is away from the leak points without the influence of leaked water. Most water accumulates around the leak points and spread outwards, thus, the velocity at the traverses closest to the leak point are the lowest.

According to the findings, both radargram comparison and velocity estimation method using equation 2 shows the effect of water leak. Apart from proving the inverse relation of GPR wave propagation velocity and the water content, the water is more likely to leak out spatially from pipe's upstream (C1 and C2) more than downstream (P1 and P2) in the longitudinal direction of the water main. It is evidenced that the drop of velocity is higher if the leak point is closer to the upstream water injection point. This phenomenon could be expressed by the dramatically higher drop of velocity in chainage X1 to X6 (leak C1) and X12 to X14 (leak C2) compared to X24 to X26 (leak P1) and X34 to X39 (leak P2). It is noted that the designed leak points C1, C2, P1 and P2 were located at X2, X14, X26 and X37 m respectively. Therefore, spread of water about leak point C1 is estimated to be more than 2.5m; while the spread of water about leak point C2 was up to 2m which spans over several GPR traverses.

4.3 Mechanisms

The four leak points represent the extents of leak in four different mechanisms expressed in Figure 11.

- Mechanism 1: No-leak/dry state

At the position away from the leak points, the sand was dry and the pipe reflection depicted as intact hyperbolic shape is clearly shown both 'before' and 'after' radargrams in Figure 12.

- Mechanism 2 : Upward water leak and spread at leak point C1 and C2

With increasing moisture content in soil due to pipe leak, the wave velocity after water injection is reduced (Figure 13a-e) at various percentages from 6.81% (smallest, 200MHz, point C1) to 22.01% (largest, 600MHz, point C2), as shown in Table 1. The phenomena are used for identifying the presence of leak points when there are changes in reflections observed in radargram and velocity estimation using equation 2. The decrease in velocity is a common indicator to prove the increase of moisture content in soil as the wave propagation was retarded. A significant change of the wave velocity of pipe reflections indicates upward spread of water because the ray-path coincided the upper part of the pipe rather than the bottom part, as depicted in the geometry in Figure 1 and 2. A previous lab experiment with a upward pre-drilled hole for leak detection shows that the reduced velocity is resulted from the spread of upward water seepage (Lai et al., 2016). Therefore, the result associated with leak points C1 and C2 are defined as the pattern for an upward spread of water leak.

- Mechanism 3: Upward water leak and spread at leak point P1 and P2

Velocity changes before and after water leak point P1 and P2 do not differ as much as those in leak point C1 and C2 ranging from 0.63% (smallest, 200MHz, point P2) to 5.25% (largest, 250MHz, point P2). It implies that the ray-path of this case was not affected as much as that in C1 and C2 after leak. However, the 'after' case in the two right columns of Figure 11 illustrates many reverberations, dis-located and distorted pipe reflections found under the first arrival pipe reflection, which is interpreted as a downward spread of water after leak. This echoes the laboratory experiment carried out by (Demirci et al., 2012) and Ko (2015) suggesting that a leak point pre-drilled at the pipe bottom would result in the changes in reverberated reflections underneath the pipe reflection. Therefore, it supports that the phenomenon found in P1 and P2 is interpreted as downward-spread of water leak.

4.4 Sensitivity of antennae frequencies on water leak detection

How sensitive is GPR on water leak detection? It is one of the primary concerns for such application as it is well-known that low frequency GPR allows deeper wave penetration but poorer resolution, and especially high resolution is required for detecting water leak. City utilities are buried at different depths and nominally within few meters underground. The shallowest is street light, telecommunication, then followed by water supplies pipe and gravity sewer pipe, and the deepest is storm drain which can be few meters underground. For common water pipe buried at about 0.5 to 1.5 m deep, the trade-off between depth ranging and resolution shall be maintained. In our study, amongst the five frequencies we used, 600 MHz antenna seems to be the most sensitive one. It is not only because it belongs to the middle frequency range giving a good balance of the said trade-off, but also because the velocity changes before and after leak are most obvious in 3 (i.e. C1, C2 and P1) out of the 4 leak points representing both upward and downward water spreading mechanisms.

5. Conclusion

The effects of water leak in a full-scale experiment have been observed by analyzing the lateral changes of GPR wave velocity and images variations in radargrams before and water leak at pre-designed leak points. With controllable water leak in pipe, the GPR wave velocity was found to drop significantly at the suspected leak points along the pipe when the water spread is upward, and plenty of reverberation appears in GPR radargrams when the water spread is downward. 600MHz GPR antenna is found to be the most sensitive one for measuring the pre-designed water leak.

Results and findings prove the appropriateness of applying GPR for identifying water leak. There are two potential applications realized in this study. First, water pipes are always required to undergo a series of pressurized test before and after commissioning for service. Comparing the radargrams and velocity changes ‘before’ and ‘after’ pressurized test can indicate if leak(s) exist or not. A 10% reduction of wave velocity using a middle frequency range GPR (e.g. 600MHz) is likely to be a sign of water leak spreading upward, and a significant reverberation underneath the pipe’s first arrival reflection is probably a sign of water leak spreading downwards. Second, for water pipe already in service but leak(s) is suspected and if the ‘before’ case is not available, comparison of lateral changes of pipeline reflections and changes of wave velocity permits tracing of multiple upward/downward leak points. It is based on the assumption that water leak does not appear everywhere along the pipe section and such variation should be able to be measured by the velocity estimation in equation 2. Likewise, the above 10% velocity threshold’s rule (upward water leak) and significant reverberation’s rule (downward water leak) also apply in this potential application. In addition to these two potential applications realized, this study also contributes to providing a fingerprint database of pipe leak tracing for field applications.

Acknowledgment

The authors thank gratefully the research funding on the project ‘Developing Ground Penetrating Radar as a Spectral Analyzer for In-Situ Evaluation of Construction Material Properties’ ‘B-Q47Z’ provided by Research Grant Council of The HKSAR Government.

References

ASTM D6432-11. (2011). Standard Guide for Using the Surface Ground Penetrating Radar Method for Subsurface Investigation. *ASTM International, West Conshohocken, PA, 2011,* www.astm.org. doi:10.1520/d6432-11

Ayala-Cabrera, D., Herrera, M., Izquierdo, J., & Pérez-García, R. (2011). Location of buried plastic pipes using multi-agent support based on GPR images. *Journal of Applied Geophysics, 75*(4), 679-686. doi:10.1016/j.jappgeo.2011.09.024

Bimpas, M., Amditis, A., & Uzunoglu, N. (2010). Detection of water leaks in supply pipes using continuous wave sensor operating at 2.45GHz. *Journal of Applied Geophysics, 70*(3), 226-236. doi:10.1016/j.jappgeo.2010.01.003

Bobylev, N. (2009). Mainstreaming sustainable development into a city's Master plan: A case of Urban Underground Space use. *Land Use Policy, 26*(4), 1128-1137. doi:https://doi.org/10.1016/j.landusepol.2009.02.003

Broere, W. (2016). Urban underground space: Solving the problems of today’s cities. *Tunnelling and Underground Space Technology, 55*, 245-248. doi:https://doi.org/10.1016/j.tust.2015.11.012

Cassidy, N. J., Eddies, R., & Dods, S. (2011). Void detection beneath reinforced concrete sections: The practical application of ground-penetrating radar and ultrasonic techniques. *Journal of Applied Geophysics, 74*(4), 263-276. doi:10.1016/j.jappgeo.2011.06.003

Cataldo, A., Persico, R., Leucci, G., De Benedetto, E., Cannazza, G., Matera, L., & De Giorgi, L. (2014). Time domain reflectometry, ground penetrating radar and electrical resistivity tomography: A comparative analysis of alternative approaches for leak detection in underground pipes. *NDT & E International, 62*, 14-28. doi:10.1016/j.ndteint.2013.10.007

Crocco, L., Prisco, G., Soldovieri, F., & Cassidy, N. J. (2009). Early-stage leaking pipes GPR monitoring via microwave tomographic inversion. *Journal of Applied Geophysics, 67*(4), 270-277. doi:10.1016/j.jappgeo.2008.09.006

Demirci, S., Yigit, E., Eskidemir, I. H., & Ozdemir, C. (2012). Ground penetrating radar imaging of water leaks from buried pipes based on back-projection method. *NDT & E International, 47*, 35-42. doi:10.1016/j.ndteint.2011.12.008

Drainage Services Department. (2016). Sustainability Report 2015-16.

Fernandes, F. M., Fernandes, A., & Pais, J. (2017). Assessment of the density and moisture content of asphalt mixtures of road pavements.(Virtual Special Issue: Ground-Penetrating Radar and Complementary Non-Destructive Testing Techniques in Civil Engineering)(Abstract). *Construction and Building Materials, 154*, 1216. doi:10.1016/j.conbuildmat.2017.06.119

Gao, Y., Brennan, M. J., Joseph, P. F., Muggleton, J. M., & Hunaidi, O. (2005). On the selection of acoustic/vibration sensors for leak detection in plastic water pipes. *Journal of Sound and Vibration, 283*(3), 927-941. doi:10.1016/j.jsv.2004.05.004

Glaser, D. R., Werkema, D. D., Versteeg, R. J., Henderson, R. D., & Rucker, D. F. (2012). Temporal GPR imaging of an ethanol release within a laboratory-scaled sand tank. *Journal of Applied Geophysics, 86*, 133-145. doi:10.1016/j.jappgeo.2012.07.016

Goulet, J.-A., Coutu, S., & Smith, I. F. C. (2013). Model falsification diagnosis and sensor placement for leak detection in pressurized pipe networks. *Advanced Engineering Informatics, 27*(2), 261-269. doi:10.1016/j.aei.2013.01.001

Hao, T., Rogers, C. D. F., Metje, N., Chapman, D. N., Muggleton, J. M., Foo, K. Y., . . . Saul, A. J. (2012). Condition assessment of the buried utility service infrastructure. *Tunnelling and Underground Space Technology, 28*, 331-344. doi:10.1016/j.tust.2011.10.011

Highways Standard Drawing H1102B. (2014). Typical Concrete Pavement Construction.

Highways Standard Drawing H1103F. (2014). Paving Units Typical Construction Details.

Highways Standard Drawing H6168 H6169 H6170. (2014). Minimum Depth Requirement for Underground Services.

Ko, Y. L. (2015). Experimental Validation of Water Pipe Leakage in Sand by Ground Penetrating Radar.

Lai, W. W. L., Chang, R. K. W., & Sham, J. F. C. (2017a). *Detection and imaging of city's underground void by GPR.* Paper presented at the 2017 9th International Workshop on Advanced Ground Penetrating Radar (IWAGPR).

Lai, W. W. L., Chang, R. K. W., & Sham, J. F. C. (2018). A blind test of nondestructive underground void detection by ground penetrating radar (GPR). *Journal of Applied Geophysics, 149*, 10-17. doi:10.1016/j.jappgeo.2017.12.010

Lai, W. W. L., Chang, R. K. W., Sham, J. F. C., & Pang, K. (2016). Perturbation mapping of water leak in buried water pipes via laboratory validation experiments with high-frequency ground penetrating radar (GPR). *Tunnelling and Underground Space Technology, 52*, 157-167. doi:10.1016/j.tust.2015.10.017

Lai, W. W. L., Leong-Ying Ho, M., Chang, R. K. W., Sham, J. F. C., & Poon, C. S. (2017b). Tracing and imaging minor water seepage of concealed PVC pipe in a reinforced concrete wall by high-frequency ground penetrating radar. *Construction and Building Materials, 151*, 840-847. doi:10.1016/j.conbuildmat.2017.06.148

Liu, Z., & Kleiner, Y. (2013). State of the art review of inspection technologies for condition assessment of water pipes. *Measurement, 46*(1), 1-15. doi:10.1016/j.measurement.2012.05.032

Loizos, A., & Plati, C. (2007). Accuracy of pavement thicknesses estimation using different ground penetrating radar analysis approaches. *NDT & E International, 40*(2), 147-157.

Metwaly, M. (2015). Application of GPR technique for subsurface utility mapping: A case study from urban area of Holy Mecca, Saudi Arabia. *Measurement, 60*, 139-145. doi:https://doi.org/10.1016/j.measurement.2014.09.064

Nobes, D. C. (2017). Ground penetrating radar response from voids: A demonstration using a simple model. *NDT & E International, 91*, 47-53. doi:https://doi.org/10.1016/j.ndteint.2017.05.007

Ocaña-Levario, S. J., Carreño-Alvarado, E. P., Ayala-Cabrera, D., & Izquierdo, J. (2018). GPR image analysis to locate water leaks from buried pipes by applying variance filters. *Journal of Applied Geophysics, 152*, 236-247. doi:10.1016/j.jappgeo.2018.03.025

Prego, F. J., Solla, M., Puente, I., & Arias, P. (2017). Efficient GPR data acquisition to detect underground pipes. *NDT & E International, 91*, 22-31. doi:https://doi.org/10.1016/j.ndteint.2017.06.002

Sagnard, F., Norgeot, C., Derobert, X., Baltazart, V., Merliot, E., Derkx, F., & Lebental, B. (2016). Utility detection and positioning on the urban site Sense-City using Ground-Penetrating Radar systems. *Measurement, 88*, 318-330. doi:10.1016/j.measurement.2016.03.044

Sham, J. F. C., & Lai, W. W. L. (2016a). Development of a new algorithm for accurate estimation of GPR's wave propagation velocity by common-offset survey method. In (pp. 104-113): Elsevier.

Sham, J. F. C., Lai, W. W. L., & Leung, C. H. C. (2016b). Effects of homogeneous/heterogeneous water distribution on GPR wave velocity in a soil's wetting and drying process. In: Institute of Electrical and Electronics Engineers.

Shangguan, P., Al-Qadi, I., Coenen, A., & Zhao, S. (2014). Algorithm development for the application of ground-penetrating radar on asphalt pavement compaction monitoring. *International Journal of Pavement Engineering, 17*(3), 1-12. doi:10.1080/10298436.2014.973027

Tosti, F., Benedetto, A., Ciampoli, L. B., Lambot, S., Patriarca, C., & Slob, E. C. (2016). GPR analysis of clayey soil behaviour in unsaturated conditions for pavement engineering and geoscience applications. *Near Surface Geophysics, 14*(2), 127-144.

Tosti, F., Ciampoli, L. B., D'Amico, F., Alani, A. M., & Benedetto, A. (2018). An experimental-based model for the assessment of the mechanical properties of road pavements using ground-penetrating radar. *Construction and Building Materials, 165*, 966-974.

Wallace, M. I., & Ng, K. C. (2016). Development and application of underground space use in Hong Kong. *Tunnelling and Underground Space Technology incorporating Trenchless Technology Research, 55*, 257-279. doi:10.1016/j.tust.2015.11.024

Water Supplies Department. (2017). *Water Security and Climate Resilient Development*. Retrieved from Hong Kong:

Xie, F., Wu, C. G.-W., Lai, W. W.-L., & Sham, J. F.-C. (2018). Correction of multi-frequency GPR wave velocity with distorted hyperbolic reflections from GPR surveys of underground utilities. *Tunnelling and Underground Space Technology incorporating Trenchless Technology Research, 76*, 76-91. doi:10.1016/j.tust.2018.02.005

Yehia, S., Qaddoumi, N., Farrag, S., & Hamzeh, L. (2014). Investigation of concrete mix variations and environmental conditions on defect detection ability using GPR. *NDT & E International, 65*, 35-46. doi:10.1016/j.ndteint.2014.03.006

Yue, D. P. T., & Tang, S. L. (2011). Sustainable strategies on water supply management in Hong Kong. *Water and Environment Journal, 25*(2), 192-199. doi:doi:10.1111/j.1747-6593.2009.00209.x