Detection and Imaging of City's Underground Void by GPR

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Abstract— **Effective ways of underground void detection and imaging by ground penetrating radar (GPR) in urban environment were studied in this paper. Through indoor laboratory validation experiments, two criterions were suggested and validated as the tell-tale sign of underground void on GPR 2D and 3D imaging. These two criterions are (1) non-continuous strong reflections in 3D slice scans, and (2) reverberation patterns with decaying amplitude in later time windows in 2D radargrams. The lab validations were further proved in line with two field studies in Hong Kong where the overlaid pavements were made of asphalt and concrete, and actual positions of voids were confirmed by subsequent ground truthing. Sources of underground noise, levels of difficulties due to different types of overlaid pavement, reasons and solutions were summarized based on the lab and field studies reported in this paper.**

Keywords — underground void detection, ground penetrating radar

I. INTRODUCTION

The unseen network of underground utilities is notably one of the few most complex man-made networks in any city. Compared to the obvious and visible damages in infrastructures like bridges and roads, problems about the existence and formation of underground cavities due to pipe leak is relatively under-estimated [1-3], until it fails and causes causalities and traffic disruption. Pipe leak causes subsurface wash-out, formation of voids and finally road collapse when the underground can no longer support the dead load and live load of the pavement structure, etc. In congested cities located in hilly terrain like Hong Kong, the water transmission and distribution networks are probably one of the most problematic issues amongst all types of underground utilities. It is because the main distribution networks always operate under high pressure and the hostile underground environment accelerates pipe deterioration. The outcome is constant underground water leaks and seepage, followed by subsurface washout of soil and eventually un-noticed formation of air-filled or water-filled underground void. Detection of such voids by efficient near-surface geophysical (NSG) method is therefore in big demand.

For any successful NSG survey on a particular type of subsurface features/problems (e.g. void detection in this study), four criteria must be fulfilled in the following sequence:

(1) Strong relationships between the dependent physical property and the features/problems (void in this study),
(2) Object under investigation is within depth of penetration of the survey method,
(3) Adequate resolution that can differentiate the feature/problems from the host materials which are soil and rock, and
(4) Efficient mobility adaptability.

Preferences of different NSG technologies applied on particular problems were prioritized [4]. Such prioritization was examined specially towards underground void in Hong Kong by [5] and major big cities after summarizing four local and international studies by [4, 6-8]. In general, for detection of subsurface cavities, resistivity, electromagnetic (EM) and GPR were rated as 'primary' methods [4]. In congested urban city like in Hong Kong, GPR and resistivity were also rated as the two most highly rated methods [5].

Such high rating of the EM and resistivity methods over the rest (gravity, magnetic, seismic, potential, polarization, etc.) can be explained in accordance with the first two criteria listed above. Firstly, the dependent physical properties of air space in cavities (resistivity, conductance, inductance, permittivity, conductivity) can be differentiated from the host materials, soil and rock. This link is a prerequisite before any inversion algorithms applied on re-construction of the detected signals to detect cavities/voids. Secondly, all EM and resistivity methods offer penetration in a range from metres to tens of metres, which is suitable to the desired depth of underground void in this study.

Amongst all preferred EM and resistivity methods, GPR is the most preferred one after reviewing the last two criteria (resolution of features/problems from the host materials and mobility adaptability). For resolution, high-frequency GPR (e.g. >600 MHz) offers a resolution up to centimeter and is able to accurately define the boundary of a subsurface void, which is not achievable by either EM induction or resistivity method. Also both EM induction and resistivity method are more susceptible to the presence of nearby metallic object, such as manhole cover and metal water pipe. For mobility adaptability commented in [5], data acquisition by GPR is superior as the data collection units can be carried in a cart or towed by a vehicle without disturbing traffic nor physical contact with the ground. On the other hand, resistivity survey requires insertion of electrodes into the ground in traditional high-resolution Wenner array's configuration. This implies that temporary traffic arrangement (TTA) is always required in the city. Therefore based on the advantages of better resolution of features/problems and fast travel speed, GPR makes itself the best candidate for underground void detection in the busy urban city.

The advantages of using GPR for mapping underground void is further elaborated as follows. Firstly, amongst common non-metallic media underground, water is the most influential factor affecting radar wave's traveling velocity and reflection strength, and absorbing high-frequency portion in spectral content because of the contrast of permittivity [9-12] Secondly, by GPR, the internal condition of the subsurface in multiple dimensions can be unfolded efficiently and in very high resolution up to centi-meter. It is because unlike acoustic methods such as acoustic emission or leak noise correlation methods, and electromagnetic induction methods (or pipe cable locating) or resistivity imaging, GPR imaging does not require any physical contact on the ground or with any objects connecting the pipe, like valves. Also compared with the seismic and low-frequency vibro-acoustics [13-15], GPR does not require physical excitation of the ground and its centi-meter resolution allows high-resolution imaging of the subsurface in urban congested underground. Lastly, GPR's wide frequency range matches different physical sizes/scales of objects in different depth ranges. For example, an antenna of 100-500MHz is suitable to study slopes within ten metres, then 400-900MHz for seawalls and roads up to several metres, and 1000-3000MHz for underground utilities and buildings structures up to several tens of centi-metres. Results based on high-frequency (>1000MHz) GPR in scaled-down experiments in the lab can therefore infer to the low-frequency GPR measurement in the field because of the insignificant velocity and attenuation dispersion across the GPR frequency range [16].

There are few previous studies using laboratory experiments and numerical modeling to investigate the potential of detecting water leak and associated road subsidence using GPR [17-19]. These studies proved the possibility of GPR mapping on underground void. Accuracy of the results may be refined and improved by advancing digital signal processing [20] and can further be extended to a detailed three-dimensional model [21].

II. VALIDATION EXPERIMENTS IN LAB

Laboratory validation in PolyU's underground utility survey lab was carried out to validate the radar patterns of the reflected signal from air-filled void. An underground void can be suspected when the following two criterion are satisfied:

(a) reverberation/ringing of the electromagnetic waves [25, 26] continue to exist but attenuated in a time window/depth not close to the surface in a radargram. This phenomenon is analogous to the sound reverberations by a string in a musical instrument within a cavity resonator, such as guitar, or to electromagnetic oscillations inside cavity resonators in high frequency electronics [25], and

(b) the reflection suggested in (a) is a local but not a continuous one in a slice image at a certain depth. A continuous reflection in C-scan is most likely due to a non-metallic underground utility (e.g. drainage pipe) but not void.

Two air-filled voids (void A and B) were excavated inside a soil tank (Figure 1) located in the Underground Utility Survey Laboratory in PolyU. After excavation, the voids were not backfilled and decked with a glass fibre panels (GRP) and surveyed with a GSSI 900 MHz antenna (Figure 1). Void A (Figure 2) was a 510-mm deep void space simulated as a manhole covered by glass fibre panel. Void B (Figure 2) was 200 mm deep, dig in the soil without any objects inside. Results of GPR radargram are shown in Figure 3. Sizes of voids A and B were 200 mm (L) x 200 mm (W) x 510 mm (D), and 250mm (L) × 220mm (W) × 200mm (D), respectively. GPR surveys were carried out on typical area 150 cm x 100 cm and a grid spacing 100 mm. As shown in Figure 3, deeper void A yields more reverberations than that from shallower void B. as a result of deeper void depth in void A (510 mm) than void B (200 mm).

Figure 1 Glass-fibre panel pavement in Underground Utility Survey Lab, PolyU and 900MHz GPR system

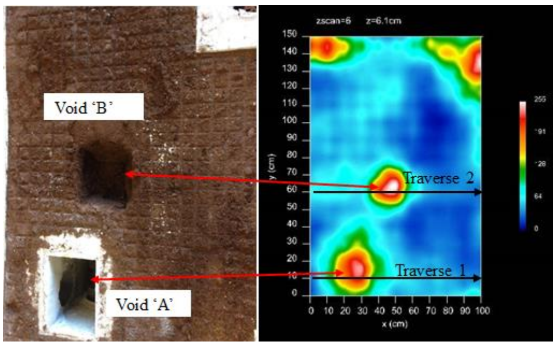

Figure 2 Photo (left) and the corresponding C-scan of voids after decking with GRP panels (right)

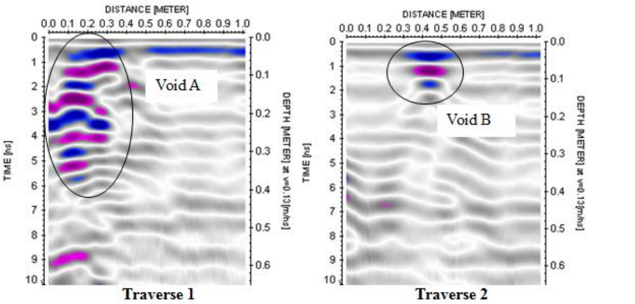

Figure 3 B-scans of 1m deep void space at y=10cm (left) and void A at y=60cm (right)

III. FIELD SURVEY

Case 1: Asphalt pavement in Bailey Street

The site locates at an asphalt pavement in Hong Kong, as shown in Figure 4. It was surveyed by a GSSI SIR-20 with 400MHz antennae following the grid pattern in Figure 5. Several areas on the rectangular grid were not surveyed because of vehicle obstruction during the time of survey. The analysis is divided into two steps. For step 1, slice scans were generated in Figure 9 and three types of peculiar features A to C with very strong reflections were qualified. Feature 'A' is suspected void manifested as *decaying* reverberation along with depth, with an important note that the reverberation does not start at time zero. Feature 'B' is the metal pit cover filled with concrete strips manifested as the *through* reverberation along with depth. Feature 'C' is the cast iron manhole cover manifested as the *through* reverberation along with depth.

Figure 4 Site plan at Bailey Street

Step 2 studies whether these features satisfy the two criterion (i.e. reverberation/ringing the decays with time window and localized reflections) as 'suspected void' stated in Section II. The qualification process was carried out by studying peculiar signals in the C-scans (Figure 6) and individual radargrams from particular traverses of interest highlighted (red arrows in Figure 5). It was concluded that only feature A is likely to be a void by the radargrams in Figure 7 because of its decaying reverberation along with depth or time window. This conclusion was later confirmed by ground truthing.

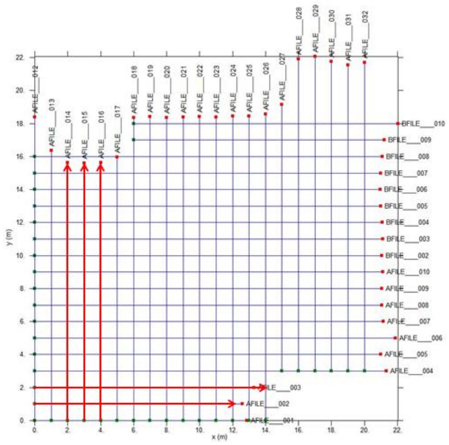

Figure 5 Gridding arrangement at Bailey Street

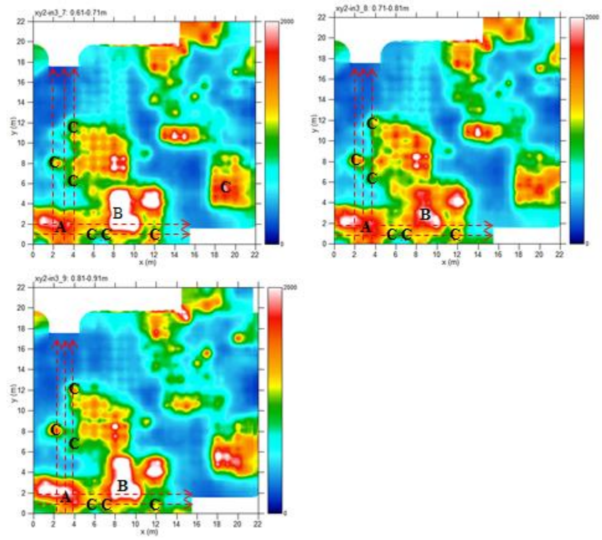

Figure 6 Slice C-scans at different depth at Bailey Street 014 (y-direction)

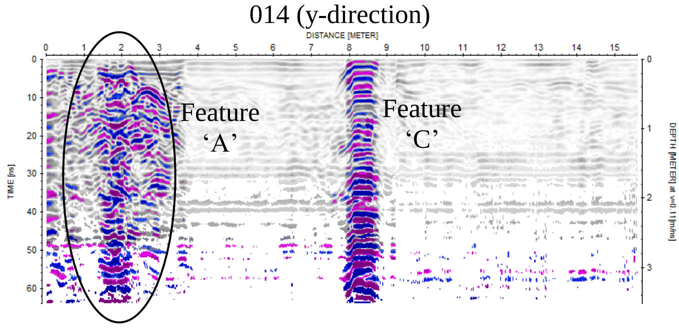

Figure 7 Radargrams showing suspected void A (type 1) at site B: Bailey Street

Case 2: A concrete platform next to a seawall in Tai O

The site is located in a concrete platform next to a temple built on A.D. 1699 and a seawall in remote area in Tai O, Hong Kong (Figure 8 and 9). The seawall was reported to be structurally defective as the diurnal tidal effects constantly erode its integrity and intrude into the bottom of the platform with seawater. The subsurface washout by seawater may leave behind voids under the platform. A damaged area next to the seawall is shown in Figure 9, left.

Figure 8 Site at Tai O

Figure 9 GPR grid pattern at Tai O and void visible from the ground (left) and void after backfill

After a comprehensive survey of the whole platform, a small area was selected to study underground voids in detail. The area was surveyed by a GSSI SIR-20 with 400MHz antennae following the grid pattern in Figure 8. The survey area covers a damage area next to the seawall (Figure 9, left) and invisible void shown later in GPR's 3D slice scans (Figure 10). The voids were qualified because the GPR imaging analysis satisfied the two criterions of underground void suggested in previous sessions, as depicted in both slice scans in Figure 10 and radargrams in Figure 11. Few months later, a re-survey was carried out as it was reported that, the damaged area was backfilled by villagers. The re-survey confirmed that the strong reflections before backfill were due to the damaged area with underground void. It was because the reverberation reflection before backfill in Figure 10 (left) disappeared compared to the weak reflection obtained after backfill in Figure 10 (right). However, the invisible void at the bottom of the survey area still exists because it was not discovered by the villagers and therefore not backfilled.

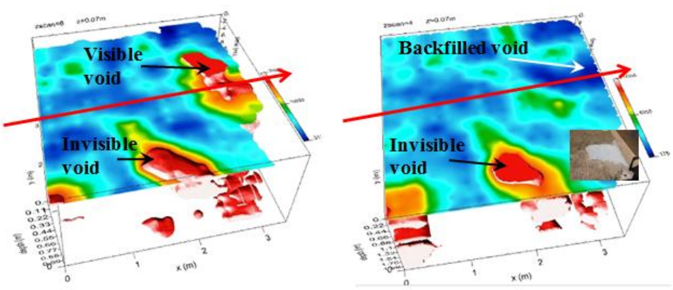

Figure 10 Slice images of the voids before and after backfill

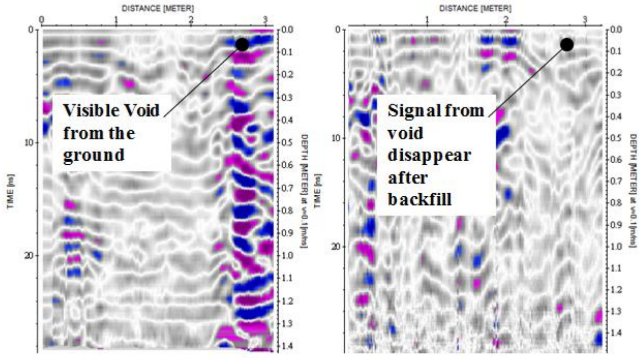

Figure 11 GPR traverse before (top) and after (bottom) backfill of void

IV. Differentiating Void from other Buried FEatures

Void detection by GPR or by other geophysical method, is a process of signal processing and interpretation by elimination. The process excludes noise induced by other underground objects or features heterogeneous to the host media (soil or rock) under a complex underground environment. The signals received by GPR carry information such as underground utilities, alien objects like backfilled cobbles or concrete fragments, underground metallic shield like ductile iron (DI) pipe, wet soil, etc. After the laboratory validation and field works of urban applications of GPR on void mapping in Section II and III, Table 1 summarizes the limitations, and rates the levels of difficulties of five common types of underground objects or features in three types of overlaid pavement materials, associated underlying reasons and probable solutions. It should be well noted that, difficulties of void detection are largely dependent on the overlaid materials, in particular concrete highway with wire mesh or steel reinforcement poses the largest difficulties on GPR survey.

V. Conclusion

The work maps air-filled voids with known positions and dimensions in three cases in laboratory and field covered by pavement made of glass fibre polymer (in lab), asphalt and concrete (in field). It was concluded that in a GPR survey, an air void can only be defined by satisfying two criterions. The first criteria is non-continuous strong reflections in 3D slice scans (C-scans), while the second is reverberation pattern with decaying amplitude with later time windows in 2D radargram (B-scans). These two criterions shall be used as a yardstick to map urban's underground void by GPR.

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References

[1] N. Metje, P. Atkins, M. Brennan, D. Chapman, H. Lim, J. Machell, J. Muggleton, S. Pennock, J. Ratcliffe and M. Redfern, "Mapping the Underworld–State-of-the-art review," *Tunnel. Underground Space Technol.,* vol. 22, pp. 568-586, 2007.

[2] Z. Liu and Y. Kleiner, "State of the art review of inspection technologies for condition assessment of water pipes," *Measurement,* vol. 46, pp. 1-15, 2013.

[3] T. Hao, C. Rogers, N. Metje, D. Chapman, J. Muggleton, K. Foo, P. Wang, S. R. Pennock, P. Atkins and S. Swingler, "Condition assessment of the buried utility service infrastructure," *Tunnel. Underground Space Technol.,* vol. 28, pp. 331-344, 2012.

[4] J. M. Reynolds, *An Introduction to Applied and Environmental Geophysics.* John Wiley & Sons, 2011.

[5] L. S. Chan, "Surface geophysical techniques for voids detection," Water Supplies Department, HKSAR Government's Consultancy Report, 2011.

[6] Drainage Service Department, HKSAR Government, "Tolo harbour sewerage of unsewered areas, stage II – investigation, design and construction. Underground void detection final rport," Tech. Rep. CE 9/2006, 2009.

[7] I. TECHNOS, "Surface geophysical methods," *Technos,* vol. 1 (1), pp. 1-19, 2004.

[8] H. Geotechnical Engineering Office, "Site characterisation study - phases 1 & 2, special project report," Tech. Rep. SPR 8/97, 1997.

[9] W. Lai, S. Kou and C. Poon, "Unsaturated zone characterization in soil through transient wetting and drying using GPR joint time–frequency analysis and grayscale images," *Journal of Hydrology,* vol. 452, pp. 1-13, 2012.

[10] W. Lai, T. Kind and H. Wiggenhauser, "Using ground penetrating radar and time–frequency analysis to characterize construction materials," *NDT E Int.,* vol. 44, pp. 111-120, 2011.

[11] J. Hugenschmidt and R. Loser, "Detection of chlorides and moisture in concrete structures with ground penetrating radar," *Mater. Struct.,* vol. 41, pp. 785-792, 2008.

[12] D. Glaser, D. Werkema, R. Versteeg, R. Henderson and D. Rucker, "Temporal GPR imaging of an ethanol release within a laboratory-scaled sand tank," *J. Appl. Geophys.,* vol. 86, pp. 133-145, 2012.

[13] J. Muggleton, M. Brennan and C. Rogers, "Point vibration measurements for the detection of shallow-buried objects," *Tunnel. Underground Space Technol.,* vol. 39, pp. 27-33, 2014.

[14] J. Muggleton and B. Papandreou, "A shear wave ground surface vibration technique for the detection of buried pipes," *J. Appl. Geophys.,* vol. 106, pp. 164-172, 2014.

[15] J. Muggleton, M. Brennan and Y. Gao, "Determining the location of buried plastic water pipes from measurements of ground surface vibration," *J. Appl. Geophys.,* vol. 75, pp. 54-61, 2011.

[16] A. Annan, "Ground Penetrating Radar Principles, Procedures, and Applications, 286 pp., Sensors and Software," *Inc., Mississauga, Ontario, Canada,* 2003.

[17] A. Stampolidis, P. Soupios, F. Vallianatos and G. Tsokas, "Detection of leaks in buried plastic water distribution pipes in urban places-a case study," in *Advanced Ground Penetrating Radar, 2003. Proceedings of the 2nd International Workshop On,* 2003, pp. 120-124.

[18] M. Nakhkash and M. R. Mahmood-Zadeh, "Water leak detection using ground penetrating radar," in *Tenth International Conference on Ground Penetrating Radar,* 2004, pp. 21-24.

[19] L. Kofman, A. Ronen and S. Frydman, "Detection of model voids by identifying reverberation phenomena in GPR records," *J. Appl. Geophys.,* vol. 59, pp. 284-299, 2006.

[20] A. E. Hasan, "The use of ground penetrating radar with a frequency 1 GHz to detect water leaks from pipelines," in *Proceedings of the 16th International Water Technology Conference (IWTC16), Istanbul, Turkey,* 2012, pp. 16.

[21] L. Dong, S. Carnalla and M. Shinozuka, "GPR survey for pipe leakage detection: Experimental and analytical study," in *SPIE Smart Structures and Materials Nondestructive Evaluation and Health Monitoring,* 2012, pp. 83470F-83470F-7.

Table 1 Rating of levels of difficulties on void detection by GPR in different pavement materials and after excluding underground objects/features

Source of noise that affect interpretation following the two qualifying criterion of underground void in Section 2	**Levels of difficulties of interpretation in different overlaid materials**			**Reasons of encountered difficulties**	**Probable solutions**
	Paving block and asphalt	Plain concrete	Concrete with wire mesh or steel reinforcement		
1. Non-metallic underground utilities (UU) like concrete or PE pipes	Relatively easy	Relatively easy to moderate	Moderate to difficult	Hyperbolic and reverberant reflections give the same pattern as void	Void manifests as local reflectors while UU manifests as continuous reflections under in slice scans in 3D representation
2. Big alien objects like backfilled cobbles and concrete fragments	Moderate	Moderate to difficult		When the object size is in the same order as the wavelength of GPR wave, wave is significantly scattered in Mie region. Cluster of these objects may also render reverberation patterns similar to void.	Apply frequency filter and adjust amplitude scale in 3D space. False alarm may still exist.
3. Underground metallic shield like D.I. pipe and bundle of wires	Moderate	Moderate to difficult		Any object beneath metallic shield like DI pipe is shielded because metallic objects reflect all energy back.	Use antenna operating in lower centre frequency, exclude the DI pipe's reflection by pipe cable locator, but such method is only possible, provided that the void is sufficiently large.
4. Different vertical road structure due to repetitive open-up and backfill	Relatively easy	Relatively easy to moderate	Moderate to difficult	Variation of signal strength in different vertical road structures makes amplitude normalization in slice scans difficult.	Apply different filters and gain curves in each individual vertical road structure, normalize the amplitude in slice scans with different scales.
5. Wet soil	Relatively easy	Relatively easy to moderate	Moderate to difficult	Water content in soil absorbs GPR wave much more significantly than dry soil does, therefore reducing depth of penetration and worsen resolution.	Though wet soil reduces the depth of penetration, the wetted layer may serve as a waveguide to improve resolution of objects.