Chapter 24

Underground Utilities Imaging and Diagnosis

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Abstract The invisible and congested world of underground utilities (UU) is an indispensable mystery to the general public because their existence is invisible until problems happen. Their growth aligns with the continuous development of cities and the ever-increasing demand for energy and quality of life. To satisfy a variety of modern requirements like emergency or routine repair, safe dig and excavation, monitoring, maintenance, and upscaling of the network, two basic tasks are always required. They are mapping and imaging (where?), and diagnosis (how healthy?). This chapter gives a review of the current state of the art of these two core topics, and their levels of expected survey accuracy, and looks forward to future trends of research and development (Sects. 24.1 and 24.2). From the point of view of physics, a large range of survey technologies is central to imaging and diagnosis, having originated from electromagnetic- and acoustic-based near-surface geophysical and nondestructive testing methods. To date, survey technologies have been further extended by multi-disciplinary task forces in various disciplines (Sect. 24.3). First, it involves sending and retrieving mechanical robots to survey the internal confined spaces of utilities using careful system control and seamless communication electronics. Secondly, the captured data and signals of various kinds are positioned, processed, and in the future, pattern-recognized with a database to robustly trace the location and diagnose the conditions of any particular type of utilities. Thirdly, such a pattern-recognized database of various types of defects can be regarded as a learning process through repeated validation in the laboratory, simulation, and ground-truthing in the field. This chapter is concluded by briefly introducing the human-factor or psychological and cognitive biases, which are in most cases neglected in any imaging and diagnostic work (Sect. 24.4). In short, the very challenging nature and large demand for utility imaging and diagnostics have been gradually evolving from the traditional visual inspection to a new era of multi-disciplinary surveying and engineering professions and even towards the psychological part of human-machine interaction.

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W. Shi et al. (eds.), *Urban Informatics*, The Urban Book Series,
https://doi.org/10.1007/978-981-15-8983-6_24

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24.1 Mapping and Imaging

One day, a patient visits a doctor describing a body pain. How does the doctor react? Will he or she immediately perform surgery or suggest a scan first to diagnose a serious health problem? Of course, the latter is the standard protocol when it comes to a doctor evaluating a patient. Unfortunately, the choice of surgery first dominates in construction work that can involve costly infrastructures such as bridges, buildings, heritage, foundations, road pavement, tunnel liners, and underground utilities. Even at home, it is not rare that someone might drill without a scan, and then inadvertently hit a gas pipe which may be damaged or even explode. An important difference between a patient and infrastructure is that a patient is more likely to take proper steps for taking care of themselves and seek out expert diagnosis, whereas the care of infrastructure which is shared by many (with most unaware of the risks and costs) is often neglected. Since the first X-ray image was captured in 1895, the diagnostic science of medicine has changed completely and become very advanced. No one would question the power of medical imaging for diagnosis and medication. But in the infrastructure world, modern scanning, mapping, and imaging methods are still not regularly practiced.

According to the Highways Department in Hong Kong, there is about 47 km of UU per kilometer of road. Such density is probably the greatest in the world. More than 20 utility companies are continually developing the underground utility network, but they occupy only the first few meters of urban underground space. In comparison with other cities, the density of underground pipelines in Hong Kong's utility network is 3.5 times greater than that of Singapore, 24 times denser than that of England, and 85 times denser than that of the United States (Wong 2014). Hong Kong and other compact cities and mega-cities probably have one of the most challenging environments for near-surface geophysical survey, mapping, imaging, and diagnosis. If the problems of UU detection in the dense environment can be solved for Hong Kong by new innovative solutions, the underground mapping problems for the rest of the world, which has the less dense underground infrastructure, will be much easier to solve.

UU accidents cause not only loss of money or valuable water resources, but also casualties such as the case of the Kaohsiung underground gas explosion in 2014 in Taiwan and the fatal Kwun Ling Lau landslide in 1994 in Hong Kong. The lack of visibility of UU and poor updating of records, in the long run, affect the design, construction, and maintenance stages of any building projects. Failures to identify the existence of UU at an early-stage can cause later design faults, leading to construction delays. The maintenance and rehabilitation of underground utilities have become difficult tasks due to the unknown location, complexity, aging, and negligence from a commonly-held mindset of "out of sight, out of mind." These factors are time bombs and increase the risk of UU damage during excavation.

In an urban area, utilities are mostly laid in a complicated manner under carriage-ways between buildings and pedestrian footpaths. Geophysical and non-destructive utilities surveys are always needed in the design, construction, or maintenance

stages of urban development and redevelopment projects in order to avoid damage to existing UU. Several international specifications or standards are currently in use. In 2003, the American Society of Civil Engineers (ASCE) published a Standard Guideline for the collection and depiction of existing subsurface utility data in the United States (ASCE 2002). Four different quality levels for detection are stated (QL-D to QL-A), which indicate the different levels of effort required. For example, QL-D refers to a statutory record search, while QL-A refers to exposing a utility through trial holes or trenches. QL-B means geophysical surveys using equipment such as electromagnetic locators (EML) and ground-penetrating radar (GPR) (Ansapach 2002).

Each of the four different quality levels represents different levels of required accuracy in defining the location of underground infrastructure. These different levels are also subdivided further into finer location requirements. There are two ways to express accuracy based on which error is greater, as shown in Tables 24.1, 24.2 and 24.3 (ICE 2014). The table indicates the reduction of location accuracy with increasing depth. Some of the higher quality levels require an absolute value of accuracy without any concern for depth. An example of the former is the British Standards Institution (BSI) which published the PAS 128:2014 standard for supplementing ASCE 38-02. Similarly, there are four quality levels for underground utility detection in the PAS 128:2014 standard. At a minimum, GPR and EML techniques are required for the quality level QL-B (ICE 2014) in Tables 24.1, 24.2 and 24.3. Another example of such expression can be found in the Competent Person Performance Monitoring Point System of the Electrical and Mechanical Services Department of the HKSAR government (EMSD). Horizontal accuracy of live power cable detection is required to be within 25% of depth. The second expression is an alternative that requires an absolute accuracy; for example, ± 150 mm, ± 250 mm, and ± 500 mm in QL-B as shown in Tables 24.1, 24.2 and 24.3. This expression is designed for shallow utilities like telecommunication cables buried at a depth in the scale of tens of centimeters. In such cases, depth-dependent accuracy would be unnecessarily stringent, given the shallow buried depth. In terms of implementation, the quality levels used to express the accuracy of detection are somehow dependent on a clients' expectation. A recent initiative in Hong Kong established a specification with simplified accuracy levels for all types of utility detection, including pipes and cables, using only PCL/EML (LSGI 2019a). The specification also follows the rationale of both expressions of accuracy, that is, a utility survey is only declared reliable if it is within the range ± 150 mm or $\pm 15\%$ of detected depth, whichever is greater. Uncertainties outside this range are declared unreliable. This accuracy level reflects a compromise after three rounds of consultation, and the need to balance technical constraints and expectations among different service providers, consultants, and clients of utility surveys.

Table 24.1 Quality level standard for underground utility detection in PAS 128:2014

Quality level on detection	Location accuracy		Supporting data
	Horizontal	Vertical	
Verification			
QL-A	±50 mm	±25 mm	Exposed the utility on verification
Detection			
QL-B1	±150 mm or ±15% of detected depth whichever is greater	±15% of detected depth	Horizontal and vertical location of the utility detected by multiple geophysical techniques
QL-B2	±250 mm or ±40% of detected depth whichever is greater	±40% of detected depth	Horizontal and vertical location of the utility detected by one of the geophysical techniques used
QL-B3	±500 mm	Undefined	Horizontal and vertical location of the utility detected by one of the geophysical techniques used
QL-B4	Undefined	Undefined	A utility segment which is suspected to exist but has not been detected and is therefore shown as an assumed route
Site reconnaissance			
QL-C	Undefined	Undefined	A segment of utility whose location is demonstrated by visual reference to street furniture, topographical features, or evidence of previous street work
Desktop utility records search			
QL-D	Undefined	Undefined	Desk study of the record drawings

Table 24.2 Recommended quality levels and accuracies of PCL/EML test/survey (LSGI 2019a)

Survey mode	Quality level	Location accuracy	
		Horizontal	Vertical
Active	Reliable	± 150 mm or $\pm 15\%$ of detected depth whichever is greater	$\pm 15\%$ of detected depth for utility buried shallower than or equal to 3 m
	Survey unreliable (SU)	Undefined	Undefined
	Survey not successful (SNS)		
Passive	Reliable	Undefined	Undefined
	Survey unreliable (SU)		
	Survey not successful (SNS)		

Table 24.3 Recommended quality levels and accuracies of GPR tests and surveys (LSGI 2019b)

Quality level	Horizontal location accuracy
Reliable	± 150 mm or $\pm 15\%$ of detected depth whichever is greater. This accuracy level is only valid if the alignment of the utility is continuously observed in C-scan
Survey unreliable (SU)	Undefined
Survey not successful (SNS)	

24.1.1 EMI/PCL

Given the worldwide use of these specifications and standards, the quality levels and accuracies required in many projects are part of contract negotiations with the clients. The actual site constraints, such as overlaid materials and interference from neighboring utilities can impact the actual quality levels that can be achieved at a site and are not considered. For example, horizontal and vertical resolution limits of the survey are rarely studied, not to mention cases for instance, like steel bars in concrete masking the EM induction signal. Siu and Lai (2019) aims to assess such subsurface conditions as well as EM coupling effects as a major source of uncertainty in electromagnetic induction studies of UU positioning. The induced electromagnetic fields from neighboring current-carrying utilities crossing each other causes interference with the detected magnetic field, as shown in Fig. 24.1.

The results of this work can provide a reference for a better understanding of the complexity of UU mapping using EML. It provides information for UU design and survey, such as minimum clearance distances between live power-supply cables and nearby metallic utilities for the sake of later positioning.

Fig. 24.1 **a** Experimental setup in HK PolyU’s underground utility survey lab: X: horizontal separation (350, 550, 750, or 950 mm) Y: vertical position (150, 300, or 450 mm); **b** estimated magnetic field shape for a cable at 150 mm depth and separated horizontally from the pipe by 350 mm

24.1.2 GPR

The second means of detection is GPR, composed of a transmitter emitting and receiving radio waves in materials at a frequency of hundreds of MHz. The basic received signals are called an A-scan waveform, and B- and C-scans are used for

GPR data presentation in two and three dimensions, respectively. A C-scan images any horizontal plane at a specified depth below the ground surface. B-scan images are vertical depth sections, and both scans provide details of the reflected wave characteristics in the medium, such as phase changes, energy attenuation, and propagation velocity. These characteristics are controlled by the properties of the host medium. Through forward and inverse modeling, the subsurface world can then be reconstructed. Normally for data collection, a series of adjacent GPR profiles have to be collected in order to determine the positions and sizes of any subsurface target. 3D C-scans are increasingly useful as they provide a straightforward and easily understandable presentation. Furthermore, other forms of 3D GPR representations were developed recently, for instance, iso-surfaces, semantic images based on energy or similarity, and feature enhancements (Böniger and Tronicke 2010a, b; Leckebusch 2003). They are all derivative presentations of fully covered measurements in 3D. A sequence of high-quality C-scans with accurate geo-referencing is essential for correctly imaging underground. However, its first use was in the 1990s (Goodman et al. 1995; Lai et al. 2018a). The parameters used for the generation of slices are mainly determined by the experience of operators, leading to inevitable human bias (Millington and Cassidy 2010) because the choice of different parameter settings may result in completely different images. GPR 3D imaging has been widely applied in diverse fields of civil engineering: for example, in mapping underground utilities (Birken et al. 2002; Lai et al. 2016; Metwaly 2015); measuring change of physical properties in materials (Kowalsky et al. 2005; Léger et al. 2014; Leucci et al. 2003); and inspecting structural conditions (Alani et al. 2013; Baker et al. 1997; Lai et al. 2012, 2013). Goodman et al. (1995) summarized the processing flow of 3D time-slice reconstruction from a series of radargrams (B-scans) and focused on three major steps: setting up the survey grid, cutting slices, and interpolation, as shown in Fig. 24.2.

But a more rigorous workflow, likewise in 2D processing (Jol 2009), was developed empirically by Luo et al. (2019) after 25 sets of field and lab experiments with ground-truthing or known object arrangements. This work established a bridge connecting GPR theories and survey practice, and balance among physical principles and constraints, acceptable imaging quality, and survey workload based on the

Fig. 24.2 **a** GPR profile spacing with a linear object: profile may be perpendicular or parallel to the object orientation; **b** illustration of slice thickness; **c** illustrations of profile spacing and radius of associated bilinear or linear interpolation, with SR_{max} and SR_{min} representing maximum and minimum acceptable search radii, respectively, while SR_y and SR_x denote the long axis and short axis of the elliptical search radius in linear interpolation, respectively (Luo et al. 2019)

Fig. 24.3 3D GPR imaging workflow based on empirical experiments. Remarks: (1) based on Eq. (24.1), where v can be determined by common offset velocity analysis (Sham and Lai 2016), f can be determined by wavelet transform (Lai et al. 2013); (2) a feature spread (Δ) denotes feature's maximum spread along a traverse

work of Jol (2009). It is necessary because unlike remote sensing from satellite-based images, the features present in GPR responses are indeed a proxy of their true appearance. Post-processing and interpretation are needed in order to reconstruct an approximation of the real feature geometry. Basically, an underground feature can be categorized into two main groups: continuous features with linear shapes, or local features with round or irregular shapes, as shown in Fig. 24.3. Continuous reflections of linear features must appear at traverses across a series of parallel radargrams. Underground utilities and rebars in concrete are two examples of buried linear features. These linear features appear as continuous reflections in C-scan displays. Local features are non-continuous structures, such as small voids or cracks, which appear in GPR radargrams as discrete reflections. The most critical factor in identifying local features from GPR C-scans is the known or estimated feature size, and if not available, estimated GPR wavelength in the medium. A good slice imaging depends also on the adequate dielectric contrast between the two materials to record a reflection.

24.1.3 Comparison Between EMI/PCL and GPR

Two of the most important and useful EM technologies for underground mapping are EMI/PCL and GPR. Compared to the most often used mechanical waves methods such as impact echo and ultrasonic, EM-based EMI and GPR technologies are superior in terms of fast data acquisition in shallow (<6 m) underground characterization. The advantages of these methods are that they do not require physical contact with the surface during measurement, unlike mechanical wave methods, which also require much longer survey times. GPR and EMI are complementary to each other (Table 24.4).

Table 24.4 Comparison of horizontal and vertical accuracy requirement in different specifications

Quality Level	Sub-QL	Survey Method	Accuracy	
			Horizontal	Vertical
QL-D	D (ASCE38-02)	Review records, Interview	/	/
	D (AS 5488-2013)	Records, Cursory Site Inspection, Anecdotal Evidence	Indicative Location	/
	D (Malaysia)	Search/collect/analyze records	/	/
	QL-D (ICE)	Desktop utility records search	/	/
QL-C	C (ASCE38-02)	Survey and plot visible above-ground utility features	/	/
	C (AS 5488-2013)	Surface Feature Correlation and Interpretation, Site survey of visible evidence	Approximate Location	/
	C (Malaysia)	Survey surface appurtenances of utilities	/	/
	QL-C (ICE)	Site reconnaissance	/	/
QL-B	B (ASCE38-02)	Geophysical Methods	Tolerance defined by the project	
	B (AS 5488-2013)	Survey and Trace	±300mm	±500mm
	B (Malaysia)	Geophysical Methods	/	/
	QL-B4 (ICE)	Detection	/	/
	QL-B3 (ICE)		±500mm	/
	QL-B3P* (ICE)		±250 or ±40% of detected depth whichever is greater	±40% of detected depth
	QL-B2 (ICE)			
	QL-B2P* (ICE)			
	QL-B1 (ICE)		±150mm or ±15% of detected depth whichever is greater	±15% of detected depth
QL-A	QL-B1P* (ICE)		Applicable horizontal survey and mapping accuracy as defined or expected by the surveyor	±15mm
	A (ASCE38-02)	Actual exposure and subsequent measurement of subsurface utilities		
	A (AS 5488-2013)	Potholing		
	A (Malaysia)	Excavate test holes		
	QL-A (ICE)	Verification	±50mm	±25mm

	(American)ASCE 38-02 Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data
	(Australia) AS 5488-2013 Classification of Subsurface Utility Information (SUI)
	(Malaysia) Standard Guideline for Underground Utility Mapping
	(UK) ICE PAS 128-2014 Specification for Underground Utility Detection, Verification and Location

* Means post-processing of signal which means GPR in the specification
 “p”

24.2 Diagnosis

Utility service lives are limited due to deterioration; and proactive assessment and diagnosis are necessary before any accidents occur. However, accidents can occur without visible signs or warnings. For example, leakage from a sewage pipe or water pipe triggers soil erosion and causes a road to collapse (Hadjmeliani 2015), or the gas leak may cause an explosion (McKirdy 2014). Such problems disturb our daily life, such as the cutting off of services. Therefore, studies are necessary for developing different technologies for condition assessment and diagnosis of underground utilities. Condition assessment results help diagnosis, which is critical to maintenance schedules and rehabilitation work for underground utilities.

Thanks to the exponential growth of computation power, many technologies have been developed and used for condition assessment of underground utilities in the past decade. Some examples are (1) high-definition videos by closed-circuit television (CCTV); (2) an advanced visual method specifically for pipeline condition assessment: sewer scanning and evaluation technology; (3) acoustic methods such as sonar techniques; and more recently (4) laser-based scanning and (5) ground-penetrating radar; (6) in-line acoustic survey.

24.2.1 *Ground-Based Technologies*

24.2.1.1 **Ground-Based Noise Logging for Leak Localization**

Apart from imaging as reported in Sect. 24.1.2, GPR is also sensitive to changes in water content in the subsurface. It can detect early-stage water leakages in different pipe materials, not limited to PVC pipes and metallic pipes, as found in 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, 2017b; Ocaña-Levario et al. 2018). GPR is widely used as a non-destructive method for detection and mapping of buried, near-surface utilities (e.g., Metwaly 2015; Prego et al. 2017; Sagnard et al. 2016). The primary reason for GPR being used in the detection of pipe-water leakages is the mechanism of dielectric polarization, where water molecules in free form contained in a material are polarized by an incident GPR wave, thus reducing GPR wave velocity. In our present research, this mechanism is used to study underground water leakages. GPR also allows efficient and fine-resolution assessment of hazards like subsurface voids and washouts (e.g., Cassidy et al. 2011; Lai et al. 2017a; Nobes 2017). This is because the physical contact between the sensors and the objects is not required in GPR, in contrast to some acoustic methods such as leak-noise correlator or pipe cable detectors (Liu and Kleiner 2013). With the wide frequency ranges that are available, various GPR antennae allow applications addressing numerous physical properties and structures in the underground environment. GPR has been used on different

pavement materials including asphalt, concrete pavements, and block pavements in road networks in most densely populated cities (e.g., Cassidy et al. 2011; Fernandes et al. 2017; Loizos and Plati 2007; Metwaly 2015; Shangguan et al. 2014; Tosti et al. 2016, 2018; Yehia et al. 2014).

The mapping of water leakage through scanning of GPR data in sliced horizontal planes is a tested approach. Because electromagnetic waves attenuate more with increasing free-water content, horizontal scans of GPR data have proven to be useful in locating leakages in water pipes in materials like sand and concrete (e.g., Lai et al. 2016, 2017b). However, the complex subsurface environment is usually densely packed with various utilities. This makes tracing the leakage or seepage of water pipes in such an environment a challenging task.

For GPR data, different velocity-estimation approaches have been proposed, including those utilizing the depth to a known reflector, velocity sounding, hyperbolic curve-fitting approaches, and estimation of GPR wave velocity assuming the value of the dielectric constant (ASTM D6432 2011). The approach of velocity analysis used in this research provides arguably a better diagnostic because it involves a comparison of wave velocities before and after the water leakage. The hyperbolic fitting method can be used to estimate GPR wave velocity from data acquired in a common offset transmitter–receiver configuration, as in ASTM D6432-11 (2011):

$$D = \frac{x}{\sqrt{\left(\frac{t_x}{t_0}\right)^2 - 1}}; \quad (24.1)$$

$$v = \left(\frac{2}{t_0}\right) \left[\frac{x}{\sqrt{\left(\frac{t_x}{t_0}\right)^2 - 1}} \right], \quad (24.2)$$

where t_x is the two-way travel time of the transmitted electromagnetic wave to the target and back to the antenna, t_0 is the two-way travel time of the transmitted electromagnetic wave to the target and back to the antenna, x is the distance between the two positions along the ground surface, and v is wave velocity (in m/ns).

Cheung and Lai (2019) compared the radargrams and velocity changes before and after the pressurized tests, to indicate if a leakage exists or not. A 10% reduction of wave velocity using a midfrequency GPR antenna (e.g., 600 MHz) is likely to be a sign of water leakage spreading upward, and a significant reverberation underneath the first arriving reflection from a buried pipe would be a sign of water leakage spreading downward. Second, for water pipes that are already in service but water leakage is suspected, if the measurements before water leakage are not available, then an examination of lateral changes in the pipeline reflections of GPR waves and changes in wave velocity would permit tracing the location of upward- or downward-spreading water leakages. This approach is based on the assumption that water leakage does not occur everywhere along the length of the pipe, and that the changes in GPR wave velocity are detectable using the equation (Sham and Lai 2016).

Noise loggers record the amplitude distribution of acoustic levels in dB. The graph record of a logger showing a sharp peak when compared with the background noise level can usually identify a point closest to the location of a possible leak. Comparing the results of multiple noise loggers at minimum flow at 2–4 am can localize the suspected leak area and extent but the exact pinpointing of the leak requires the following leak locating and pinpointing methods.

24.2.1.2 Ground-Based Leak Noise Correlation (LNC) for Leak Locating and Leak Pinpointing

A leak noise correlator is an electronic device used for pinpointing leak(s) in pressurized water or gas lines. Typically, two or more microphones or acoustic sound sensors are put in contact with the pipe at two or multiple points of access. The device records the sound emitted by a leak (e.g., a hissing noise) between the contact points by using the pipe as an acoustic waveguide. The sound data is processed to correlate the two recordings to determine the time difference that the noise takes to travel from one sensor to the others. Distance between the sensors is required to be known in advance for estimating the leak point. The cross-correlation signal of one continuous function with another is defined as

$$(f * g)(t) = \int_{-\infty}^{\infty} f * (\tau)g(t + \tau), \quad (24.3)$$

where f^* is the complex conjugate of f , and f and g are the two sound recordings of the noise produced by the leak, if any. The time delay can be found by estimating the time offset for which the cross-correlation product $(f * g)(t)$ reaches a maximum. When more than two sensors are used, the correlation process can be conducted at multiple sensor stations. This approach is accurate as long as the sound of the leak received at each sensor is adequately similar over a period of time, say a few minutes. After estimating the time delay of a leak, any leak correlators require (1) the sound travel velocity and (2) the prior measured length between the two access points, for identifying the exact distance of the leak from the sensors. For leak localization, the sound velocity depends on the size and material types of the pipe, which are standard inputs in most LNC devices. For leak pinpointing, it requires that the alignment of the pipe is determined by another method: pipe cable locating or electromagnetic locating. Leak detection is only accurate when these two methods provide a confident cross-correlation.

Leak noise correlator (LNC) and pipe pigging are widely adopted methods to detect water leakages by calculating the variances in time delay and predicting the speed of acoustic waves in the pressurized water pipe networks (Hao et al. 2012). LNC requires recording of leakage-induced noises under circumstances where sound and vibrational disturbances are negligible during the detection process. The LNC

method, like all non-destructive testing methods, is limited due to a number of factors such as limited coupling of the pipe with the surroundings, inadequate pressure, and variation in pipe material and pipe size (Gao et al. 2005; Hao et al. 2012). In some cases, such as in the early-stage water leakages in gravity pipes, leaking pipes that have lost pressure or large-diameter trunk pipes, where acoustic wave transmission is considered to be unfavorable, the location of leakage points has not been possible (Gao et al. 2005; Hao et al. 2012; Liu and Kleiner 2013).

24.2.2 *In-Line Technologies*

In-line technologies mean putting sensors directly inside the utilities and letting the fluid (water and gas) drive the sensors automatically. These technologies avoid attenuation due to increasing depth and loss of resolution in the ground-based technologies. There are several methods for in-line condition assessment of pipelines available in the market. The following section will focus on those used by the largest group of agencies in the pipeline industry. The riskiest method is always that requiring human entry into the underground environment, and the application of the following methods reduces that need.

24.2.2.1 Closed-Circuit Television (CCTV)

Closed-circuit television (CCTV) is the commonest technique for pipeline condition assessment. The apparent advantage of CCTV is that it is a technically simple method that can directly capture illuminated images of defects on the pipe's interior wall. When necessary, the captured images can be examined in detail by further zooming the camera from different angles by controlling the tractor. CCTV was first introduced in the 1960s for the inspection of pipe interiors, and it consists of a small optical camera mounted on a tractor, which is a self-propelled platform with wheels. Nowadays, high-definition cameras permit the capture of better images for interpretation, and the system is remotely controlled by an operator on the ground surface. The natural limitation of CCTV is that it can only be applied above the water's surface, and the movements of CCTV tractor along the pipe may affect the quality of captured images (Kirkham et al. 2000). Besides, it can only determine defects that are already exposed on the surface of the pipe's interior wall. The interpretation of collected images is highly subjective, largely depending on the experience of the interpreter; any factors such as uneven and inadequate lighting may also affect the interpretation. About 2% of the main sewer network in the UK had been inspected by 2004 and at least 20% of those observations obtained by CCTV inspection were thought to be inaccurate (OFWAT 2004).

24.2.2.2 Sonar Techniques

Sonic techniques can be used to measure mass loss of exposed steel due to corrosion, and can also identify the deformation of pipes and the volume of debris inside a pipeline. The basic principle of sonar techniques is that a sound wave is excited from a transmitter, and the time for transmission and reflection is measured. The distance between the transmitter and the target can then be estimated by using the speed of sound traveling in the medium, for example, water; from this information, a sonar profiling image of a pipe's interior condition can be constructed and assessed (Hao et al. 2012). The advantage of sonar techniques is that they are not limited to pipelines that are free of fluids, which largely removes the cost of dewatering and reduces the possibility of uninspected pipelines (Schrock 1994). It is important to note that sonar images captured above and below the water surface should be constructed and interpreted separately because the traveling speeds of sound in air and water are different (Eiswirth et al. 2000).

24.2.2.3 Sewer Scanning and Evaluation Technology (SSET)

Optical scanner and gyroscope techniques were adapted for pipe-interior inspection in the late 1990s, integrated as sewer scanning and evaluation technology (SSET), and specially developed for pipe-interior condition assessment. Unlike CCTV, SSET allows defect interpretation after the device has finished running through the whole length of the pipe. There are studies in the literature on automating the assessment process in order to increase the efficiency and interpretation accuracy (Chae and Abraham 2001). Similar to CCTV, SSET also involves the interpretation of visual images collected by the device and only surface defects can be assessed. Therefore, SSET has recently been combined with other inspection techniques such as ground-penetrating radar (GPR; Koo and Ariaratnam 2006).

24.2.2.4 Laser-Based Scanning

Laser-based scanning started to be employed for pipeline inspection in the early twenty-first century. The basic principle of laser-based scanning is that it will continuously generate a laser beam, which is projected around the pipe-interior. It highlights and profiles the crown shape at each point along the pipe alignment (Read 2004). The limitation of laser-based scanning survey is that it can only be used reliably above the water surface. Recently, 3D laser scanning and modeling have been developed, which makes it possible to provide a 3D profile of the pipe (Garvey 2012).

24.2.2.5 Infrared Thermography

Sham et al. (2019) presented a first case study of customizing an in-pipe infrared thermographic system built in-house (IPITS). It makes use of thermo-images for

imaging and diagnosis of pipe crown conditions in underground sewer pipelines. Active and passive infrared thermography (IRT) was attempted in two gravity sewer pipes in Singapore in July 2017. The results show that images captured with active IRT (with heating) can reveal the invisible lining defects not readily revealed by traditional visual inspection using CCTV. These defects include delamination and bubbles, water seepage, wrinkling, or construction details (like anchor knobs in the inspected HDPE material), for which sizes were estimated using an image-processing algorithm customized in an in-house program. The results are believed to pave the way for parallel inspections using a combination of CCTV and infrared cameras in composite-lined pipelines.

24.3 Future Trends of Research and Development

24.3.1 Multi-array and Fully Automated GPR

The single-channel GPR system discussed above is restricted by its limited underground footprint over a particular traverse; hence multiple traverses in x - y planes are required to generate an underground 3D image. With the advent of instrumentation and improved computer processing power, antenna arrays can be formed by aligning multiple antennae to cover a larger footprint. The advantage of this setup is that it allows the survey of a wide section in a single traverse, which can even be accomplished at highway speeds; thus it avoids tedious temporary traffic blockage and bureaucratic procedures as required in single-channel GPR imaging. Also, the configuration of the array is flexible, and spacing between antenna and number of channels can be user-defined to achieve the necessary resolution required for a survey. In addition, while the traditional pulse-GPR used a fixed center frequency and was limited to a certain bandwidth, new GPR arrays include step frequency continuous wave (SFCW) technology, which generates almost a flat response over a wide bandwidth (e.g., 10–1500 MHz). This newer setup can image satisfactorily at multiple depths and multiple resolutions in a single traverse.

24.3.2 In-Line Robotic Imaging with Micro-robots Carrying Small Sensors in Pressurized and Gravity Utilities

An increasingly popular type of in-line technology for condition diagnosis uses an installed inspection tool as an alternative for minor leaks and seepages that are not detectable by ground-based technologies in a pressurized utility, such as in-line acoustic emission (AE). When AE sensors are inserted in any pressurized water utility, leaks and defects can be detected following the same principle as the noise logger and LNC. This overcomes most of the ground-based AE's limitations and

can reach the defective area directly. The in-line AE tool may consist of an acoustic hydrophone, magnetometer, gyroscope, accelerometer, and an internal power-supply, or in some cases, may employ free-swimming within the utility without power. The in-line AE tool, with appropriate water-proof and dust-proof housing, is conveyed through the utility and is driven by the flowing current without disrupting normal service. The quality of the in-line AE tool, the transport medium, and the current (water or gas) transmission velocity control the sensitivity. For an exact pinpointing of the leak or defect within the utility, the in-line AE tool is driven by the flow current, in which chainage is measured by an odometer wheel or regular time tag. The start (insertion), intermediate (tracking), and end (extraction) nodes (e.g., air valves) must be geo-referenced with GPS or topographic surveys.

24.3.3 Multi-disciplinary Research on Sensors, Robotics, Electronics, Pattern Recognition, and Change Detection

For any successful utility mapping, imaging, and diagnosis, there are three key technological elements:

Physics Sensors such as an antenna array, an induction coil, a piezoelectric device, CCD, a laser, or an echo sounder have to be designed to compromise (1) the survey purposes of imaging and diagnosis, and (2) its interaction with the utility material properties or media around the utility, such as attenuation, resolution, scattering, and environment. Results should be within reasonable ranges of uncertainty and acceptable levels of accuracy in the above-mentioned two modes of the survey: (1) ground-based technologies where the sensors and the utilities are remotely separated by materials like soil, and (2) in-line technologies where the sensors are directly driven by fluid flow along with the utilities.

Robots and electronics Current surveys have limited efficiency because of insufficient sampling of data resulting from the manual nature of the operation. For full-field utility imaging and diagnosis, the underground's confined space and its large volume of captured data require robots carrying sensors and electronics for seamless positionings, like an inertia motion unit (IMU), simultaneous localization and mapping (SLAM), and wire or wireless communication between the ground control station and the sensors.

Pattern recognition and change detection Comprehensive databases of signatures of subsurface defects are required to define defects as diagnostics for pattern recognition. Matching of physical methods and failure modes due to utilities are required: for example, GPR and void, IR and delamination, PCL/EML and pipe alignment, CCTV and surface defects, etc. With the matching defined in a database, operators will be liberated from the massive amount of data interpretation. Next, change detection enables establishment of a medical record of underground utilities with a series

of time-lapse utility imaging and diagnosis, for extracting development of potential subsurface defects longitudinally rather than when failure happens. A successful pattern recognition system should be able to distinguish (1) true positive (TP; i.e., identified defects do exist) and false negative (FN; no defects identified and confirmed after ground-truthing); and (2) false alarm: true negative (TN; i.e., identified defects do not exist) or false positive (FP; defects exist but are not identified).

24.3.4 Utility Lab

An underground utility survey lab is very much in need for research on these topics. In the Department of Land Survey and GeoInformatics of the Hong Kong Polytechnic University, a lab was designed and built and has been in operation since July 2014. Scale-down networks and a matrix consisting of metallic and non-metallic fresh and saltwater supply pipes, drainage, and sewerage pipes connected with manholes, power cables, and gas cables, and valve chambers of various kinds are embedded in a big tank in the lab. These networks of underground utilities and back-filled soil serve as a scaled-down model comparable to actual field conditions. The lab provides an indoor and controllable environment where orientations, depths, sizes, material types, and coordinates of various utility networks are carefully designed and recorded. All these attributes are geo-referenced and integrated into a geographic information system.

Students and practitioners can operate various survey instruments to position and map the networks and the matrix of underground utilities and other objects, as well as to carry out condition surveys, and assessment and monitoring with advanced nondestructive instrumentation and software. The instrumentation includes ground-penetrating radar, electromagnetic induction, acoustic leak-noise correlation, noise logger, etc. The software consists of commercial and programs developed in-house, which support signal processing and multi-dimensional subsurface imaging of the collected electromagnetic, acoustic, and thermographic signals. In the lab, users can practice with the survey instruments, software, and standard survey procedures; understand what can and what cannot be done; and understand the relationships between accuracies and uncertainties of each survey method and any particular problem. Such an indoor and controlled environment enhances the confidence of students and practitioners who carry out underground utilities surveys, assessment, and monitoring in actual site environments, where most utilities are unseen and accuracies of records are not guaranteed.

The lab also serves as a hub to validate non-standardized survey methods and procedures for particular problems in two categories. The first is positioning and mapping, such as orientations, depths, sizes, and material types of utilities. The second is condition survey, assessment, and monitoring, including the effects of water leaks, subsurface voids, soil types, and moisture content, and coverage of concrete and asphalt structures for various types of survey signals. Each individual validation

between any particular survey technology and any particular problem characterizes itself via the provision of the signal fingerprints. These validated fingerprints in the lab serve as a basis for pattern matching in actual field surveys. The lab is an essential step to substantiate any interpretation of imaging and diagnostic findings. The setting in the lab provides an ideal environment for such a validation process for better interpretation of positioning, mapping, condition survey, assessment, and monitoring of the very complicated and congested underground utilities in urban areas (Fig. 24.4).

24.4 Conclusion and the Way Forward

This chapter has reviewed the current state of the art's technologies of underground utility mapping, imaging, and diagnosis, and future trends of development, namely sensor physics, robotics and electronics, and pattern recognition and change detection. These are all still relatively new areas for practical imaging and diagnosis.

A literature review always tells of the successful rather than failed case studies of utility imaging and diagnostic applications in various underground problems. However, in reality, it is very normal for survey results to be less than satisfactory, especially when the introduced technologies are inappropriately carried out in commercial contracts. If one attempts to look beyond the successes, one finds that at least one or a combination of the following five factors (abbreviated to 4M1E) account for the outcome of those unsatisfactory results.

- Men (and women): qualified personnel who are trained and experienced
- Methods: procedures of data collection, processing, and interpretation
- Machines: functions, calibration, and verification in a fixed period of time
- Material: wave attenuation, resolution limits, wave scattering, etc.
- Environment: temperature, humidity, visibility, site constraints, etc.

These problems give rise to many opportunities for research and development, and can loosely be divided into the human (24.4.1) and technological (24.4.2) perspectives corresponding to 4M1E, leading to research and development opportunities.

24.4.1 *Human-Factor Perspective*

The first and the most important reason for the less than satisfactory cases is the first M, the staffing factor, which is more or less related to human factors and associated errors; for example, manipulation of an intensity scale for drawing favorable but not genuine conclusions. Urban geophysics for underground object imaging is becoming a regular technology, rather than one carried out by a small group of elite researchers. Its nature is similar to the function of radiographers assisting medical doctors in

making diagnoses for patients. But these crucial yet arbitrary functions always require indirect evidence and human judgement, which are heavily dependent on perception of the tasks and cognitive biases. They are often the least considered factor in the scientific community and in practice.

Yet they can be more important than, or at least as important as, the other uncertainties in other Ms and E. So, a blind test is the most efficient method for evaluating the capability of staff (Lai et al. 2018b). Research on the blind test's rationale aims (1) to identify and understand the common cognitive biases in the blind test systematically, (2) to investigate the effect of corresponding cognitive biases on the quality of decision-making, and (3) to establish a bias-alleviation model and guideline with debiasing techniques specific for the blind test exercise on any tasks in utility imaging and diagnosis. In practice, regular certification and accreditation of service providers can also help to alleviate part of these problems.

24.4.2 Technological Perspective

Biases from human judgment or survey setting can be reduced but not completely, and therefore doubts arise about imaging and diagnostic purpose. Apart from multi-disciplinary hardware research (sensors, robotics, and electronics), systematic, bias-free, automatic, or semi-automatic workflow for urban underground diagnosis based on forward and inverse methods is surely the way forward. Development of methods integrated with image processing algorithms for extracting spatial and temporal features (i.e., hazards) from utility-surveying methods are of utmost importance because of the large amount of data and point clouds. The process imitates the decision-making process normally made by skilled professionals but in a semi-automatic and more robust fashion, especially when even the most skilled professionals would fall short in their ability to handling huge volumes of data.

This initiative contributes to the research, engineering, and surveying community in the following four aspects for each of the utility imaging and diagnostic methods described in the sections above. First, object- or hazard-oriented workflow for generalizing reliable images should be developed, with empirical, statistical, or learned thresholds and ranges of identified and crucial parameters. The workflow should be validated after comparing images and reality through ground truth. Secondly, the responses of underground hazards, for example, void, leak, pipe wall thinning, should be quantitatively analyzed with laboratory and fieldwork. Thirdly, a workflow integrating pattern recognition techniques should be developed to identify hazards automatically or semi-automatically and suggest rates of true positives. Last, development of a workflow is required to identify temporal changes from time-lapse datasets with change detection techniques commonly used in remote sensing, for example, *k*-means clustering to classify pixels into changed or unchanged. These four directions provide a gateway towards reliable and consistent imaging and diagnosis, and a basis of time-lapsed comparison with a well-established pattern recognition database. In short, this research and development direction, if implemented in practice, will

establish a healthy diagnostic approach for the urban underground, so that human subjective interventions and other unfavorable factors in 4M1E are reduced as much as possible.

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