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A review of Ground Penetrating Radar Application in Civil Engineering: a 30-year journey from Locating and Testing to Imaging and Diagnosis

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Abstract

The GPR (Ground Penetrating Radar) conference in Hong Kong year 2016 marked the 30th anniversary of the initial meeting in Tifton, Georgia, USA on 1986. The conference has been being a bi-annual event and has been hosted by sixteen cities from four continents. Throughout these 30 years, researchers and practitioners witnessed the analog paper printout to digital era that enables very efficient collection, processing and 3D imaging of large amount of data required in GPR imaging in infrastructure.

GPR has systematically progressed forward from “Locating and Testing” to “Imaging and Diagnosis” with the Holy Grail of 'Seeing the unseen' becoming a reality. This paper reviews the latest development of the GPR’s primary infrastructure applications, namely buildings, pavements, bridges, tunnel liners, geotechnical and buried utilities. We review both the ability to assess structure as built character and the ability to indicate the state of deterioration. Finally, we outline the path to a more rigorous development in terms of standardization, accreditation, and procurement policy.

Keywords: ground penetrating radar (GPR)

1. Introduction

One day, a patient visits a doctor describing a painful wrist. The doctor says “Well! If you are not feeling well, how about we drill a hole in your wrist, have a look and take some samples?” If you were the patient, would you let a doctor do invasive surgery without a scan, like magnetic resonance imaging (an MRI scan) or computer X-ray tomography (a CT scan)? Unfortunately, this happens every day in construction work involving costly infrastructure such as bridges, buildings, heritage, foundations, road pavement, tunnel liners, and underground utilities. Even at home, someone may excavate without a scan, hit gas pipe which may explode causing casualties. The only difference between a patient and infrastructure, is that a patient is more likely to be aware of proper steps to take care of themselves whereas infrastructure care is shared by many (with most unware of the risks and costs). Since the first X-ray image was captured in 1895, the course of diagnostic science of medicine was changed completely. No one questions the value of medical imaging. But in the infrastructure world, many are still not aware of the modern scanning methods available and never even consider imaging before invasive investigation!

Analogous to medical imaging, GPR is one of the most popular near-surface geophysical methods adopted for infrastructure imaging. GPR instruments transmit radio wave signals into a material structure and detect the echoes from changes of material properties within the structure. Most often the radio wave signal is formed as a short pulse of electromagnetic (EM) energy. The GPR signal contains a broad range of frequency components and is typically in the 10 to 5000 MHz range. For this reason, GPR instruments are referred to as ultra-wide band (UWB) radio wave devices. The GPR signals are representation of EM waves formed of coupled electric and magnetic fields propagating into a material. Changes in the electric and magnetic properties of the material scatter and reflect the EM waves. The GPR receiver detects these scattered and reflected signals and provide the basis for imaging into a structure that is opaque to eye. With advanced signal processing and image re-construction techniques, these received signals are transformed into a 3D subsurface image enabling 'seeing the unseen'.

Popularity of GPR is probably best explained by the following two reasons. First, the internal variability of a structure can be efficiently discerned with quick data acquisition and immediate on-site feedback. The image resolution can be on the scale of centimeter depending on the GPR system bandwidth. This resolution scale is a good match for the scale of mapping the need of infrastructure assessment.

The advent of GPR started in the field of geo-science after mid-1950s, and is gradually adopted in civil engineering since mid-1990s. After 2000, technological advancements and tremendous improvements of digital computation power have blossom the GPR applications on infrastructure. It is of little doubt that GPR applications are progressing from traditional locating, testing and evaluation of objects in small scale to imaging and diagnosis nowadays. The development has paved the way to large-scale and regular use of the technologies in almost all types of infrastructures in future decades. The progress is particularly reflected in the wide use of 3D imaging (C-scans or slice scan) in addition to traditional 2D imaging (B-scan or radargram), an attribute indicated in the tables of various applications in this paper. This development opens a doorway of a relatively novel horizon of interpretation and diagnosis. But still, both 2D and 3D imaging are somehow an arbitrary process dependent on subjective judgement, that the greyscale does not directly indicate any inversed parameters like the similar case in remote sensing, where m/s, temperature, etc, are measured. So manipulation of this scale can still give a very different results and misleading interpretations, which require high expertise levels. Objective guidelines of imaging parameters are yet to be studied and standardized.

GPR emits radio wave energy and for many years, GPR was used without regulatory limits and to some degree could be construed as illegal radio transmitters. Most GPR devices were of very low power and did not consider a significant source of interference. As with all devices that generate electromagnetic signals, regulatory bodies saw this growing area of use and initiated oversight rule making. GPR is now regulated in most parts of the world as an ultrawide-band (UWB) device with specific power, frequency, and usage limitations. The degree of rule-making advancement and enforcement varies greatly. Regulatory offices with clear standards are the U. S. Federal Communications Commission (FCC) FCC 47 CFR Part 15 subpart F [1], Industry Canada (RSS220) [2] and the European Telecommunications Standards Institute (ETSI EN 302-066 V2.1.0) [3]. The FCC review started in 1998 and resulted in rulings in 2002, the ETSI process took longer and ended in 2008 and in Canada the process ended in 2009. While stable regulatory environments now exist, the rules are open to change (ETSI standard revision is occurring at the time of this writing).

The year 2016 marks the 30th anniversary of the GPR conference since the first official sequence of meetings commenced in Tifton, Georgia, USA (1986). Several meetings occurred prior to and during the bi-annual sequence that are not part of the standard list with the most seminal one being in Ottawa in 1988 (Pilon,1992) which formally adopted the name ‘ground penetrating radar’ from the many terms being used for then technique at the time. Also since 2001, a much small scale International Workshop of Advanced GPR (IWAGPR) has been started in Europe. A list of the GPR conferences is as follows:

- 16th International Conference on GPR 2016 at Hong Kong; Chair: Wallace W.L. Lai, The Hong Kong Polytechnic University, Hong Kong.
- 15th International Conference on GPR 2014 at Brussels, Belgium; Chair: Sébastien Lambot, Université catholique de Louvain, Belgium.
- 14th International Conference on GPR 2012 at Shanghai, China; Chair: Xiongyao Xie, Tongji University, China.
- 13th International Conference on GPR 2010 at Lecce, Italy; Chair: Raffaele Persico, IBAM CNR, Institute of Archaeological & Monumental Heritage, Italy.
- 12th International Conference on GPR 2008 at Birmingham, United Kingdom; Chair: Chris Rogers, School of Civil Engineering, University of Birmingham, UK.
- 11th International Conference on GPR 2006 at Columbus, Ohio, USA; Chair: Chi-Chih Chen, ElectroScience Laboratory, Ohio State University, USA.
- 10th International Conference on GPR 2004 at Delft, the Netherlands; Chair: Evert Slob, Delft University of Technology, The Netherlands.
- 9th International Conference on GPR 2002 at Santa Barbara, California, USA; Chair: Steven Koppenjan, Bechtel Nevada/Special Technologies Laboratory, USA
- 8th International Conference on GPR on 2000 – Gold Coast, Australia; Chair: David Noon, Groundprobe Pty Ltd, Australia
- 7th International Conference on GPR 1998 – Lawrence, Kansas, USA; Chair: Richard Plumb, Univ. of Kansas, USA

- 6th International Conference on GPR 96 – Sendai, Japan; Chair: Motoyuki Sato, Tohoku University, Japan
- 5th International Conference on GPR 94 – Kitchener, Ontario, Canada; Chair: Davis Redman, Sensors & Software, Canada
- 4th International Conference on GPR 92 – Rovaniemi, Finland; Chair: Pauli Hanninen, Geological Survey of Finland, Finland
- 3rd International Conference on GPR 90 – Lakewood, Colorado, USA; Chair: Gary Olhoeft, Colorado School of Mines, USA
- 2nd International Conference on GPR 88 – Gainesville, Florida, USA; Chair: Mary Collins, University of Florida, USA
- 1st International Conference on Ground Penetrating Radar 1986 – Tifton, Georgia, USA

Formal designations of 1st, 2nd and 3rd etc were attached without full reference to prior activities and as such the first true GPR conference is always the subject of debate. Other GPR Conferences/Meetings prior to 1990 include International GPR meeting (1988), Ottawa (Chair: Jean Pilon, Geological Survey of Canada), GPR conference/meeting (1984) at Delft University (Chair: Richard Yelf and Peter Ulriksen of Lund University in Sweden), and GPR conference/meeting (1978, or late 1977) (Chair: Jamie Rossiter, Ocean engineering research institute in Newfoundland, Canada)

The three authors of this paper offer readers different perspectives of GPR applications on fast-growing and aging infrastructures in Asia, Europe and North America, and also perspectives from university, research institute and equipment manufacturer. It serves as a guide for civil engineers/surveyors, geophysicists and GPR practitioners/researchers on the development of

GPR in the past 30 years. The content is divided according to the types of infrastructures, namely buildings, road pavement and bridges, tunnel liners and geotechnical applications, underground utilities, and finished with two universal topics that contribute to applications of various kinds: material properties as well as method validation, accreditation, specification and procurement.

2. The Physical Principles

GPR systems typical operate in the 10 to 10,000 MHz frequency range The antennas that are used to emit and detect the signals must have dimensions comparable to the wavelengths of the signals which ultimately defines the size of the GPR instrument. GPR's operating in the 10-100 MHz range are suitable for imaging deep foundations on the tens of meter scale; GPR's in the 100-1000MHz are used for investigate road pavements, tunnel liners and utilities on the meter scale, and GPR's in the 1000-5000 MHz range are used for tunnel liners and building structures assessment on the centimeter scale.

As stated above, the GPR signals are electromagnetic waves which penetrate into the material structure under investigation. Electromagnetic waves consist of electric and magnetic vector fields which travel as wave through the material. The speed of travel, the attenuation, the polarization changes and redirection of signals are defineed by variations in the electric and magnetic properties of the material

Soils, rocks and biomass which often form construction materials are generally considered lossy dielectric media normally composed of a mix of components. For example, a simple soil will contain mineral grains, air, water, and biomass. Electrical charge mobility in the material components is variable but is limited, giving rise to polarization behavior which defines the effective dielectric and conductivity of the bulk medium. The electrical properties are generally dominated by the presence of water. Electrical charge mobility depends on the distance charge moves (since there will be path obstructions which block or impede movement). Distance travelled in turns depends on the time duration of the electrical forces applied. Rapid alteration of applied field will thus see less impediment to charge movement and the material will appear to have a higher electrical conductivity and lower dielectric permittivity as the oscillation frequency of the field increases. In many instances the change with frequency can be characterized as dipolar polarization mechanisms which have a range of relaxation frequencies or response times.

A simple polarization mechanism with a single frequency or response time has been described by Debye [4]. Water is good example of a Debye type material with a molecular rotation relaxation frequency of about 10 GHz. Composite materials tend to have a distribution of response times or relaxation frequencies and distributed models have been described by Cole and Cole [5]; Ulaby, [6]; Von Hippel [7]. For geologic materials and construction materials, there are two dominant behaviors; Maxell Wagner type polarizations [8] which occur in the 10 to 10 MHz frequency range and the water relaxation at 10 GHz. There are few polarization relaxations in the 100 to 2000 MHz range where the predominant use of GPR occurs. In this frequency range, velocity and attenuation dispersion are comparatively small creating the GPR plateau [9]. This observation explains the effectiveness of GPR and the efficacy of time domain reflectometry determining the dielectric properties of materials [9-11]. With this general understanding, researchers and practitioners are not required to start over when the investigation target and material changes, such as from concrete buildings to underground utilities, or from geoscience to infrastructures. This basic understanding underpins the utility of GPR and allows a commonality of communication amongst the practitioners in many application areas. For this reason, different disciplines of geo-science and engineering share a common interest in the use and advancement of GPR.

3. Engineering Geophysics and Inversion

Applied geophysics encompasses a wide range of methods whereby signals and fields observed at the earth's surface are used to infer the subsurface structure and composition. The observable fields range from static such as the earth's gravity and magnetic fields to dynamic such as time varying stresses and strains associated with elastic waves. GPR applications exploit time varying electromagnetic fields at radio frequencies. When these methods are applied in the field of civil and structural engineering, the applications are referred to as engineering geophysics. In this context the term 'earth' is replaced by the word 'structure' but the objective is the same and fundamental principles are not identical.

On the last several decades, GPR has been widely studied and enhanced for numerous sub-surface geophysical applications with links to civil engineering; this section can only provide an overview of the most significant scientific productions. Several textbooks demonstrate this evolution [12-15]. In a similar way, Davis and Annan [9] and Slob et al. [16] provide overviews of the method evolution in scientific publications.

When studying the propagation of radar waves in soils, the velocity and attenuation are governed by the geometric spreading and the material EM characteristics (the relative effective permittivity, including the material-attenuation losses). Numerous geophysicists studied the electrical properties of various sedimentary soils, mainly clay and silty soils or rocks, function of water content showing the attenuation and dispersion effects versus frequency [6, 7, 10, 17-20].

The number of applications, from geology and sedimentology, aquifer characterization and hydrology, mining, permafrost, geotechnical and environmental problems, in addition to archaeology, agriculture, utility or unexploded ordnance (UXO) detection, and at last forensic investigations, demonstrate the multi-use and adaptability of GPR. Amongst the applications, estimation of soil water content remains the most studied application, Huisman et al. [21] gives a good overview on GPR techniques developed for it. In that frame, such estimation from dielectric constant measurements using homogeneous models, as Complex Refraction Index Model (CRIM), being not sufficient [22], Topp et al. [10] proposed a classical empirical third order equation linking dielectric constant with water content in a large variety of soil types. These models form basis of water content estimation in construction materials in infrastructures.

Nevertheless, it is interesting to focus on the evolution of GPR data processing, modelling and inversions in the last three decades, applied on these numerous geophysical applications. Most of these methods come from seismic techniques and were adapted to radar waves [23]. To detect and localize subsurface objects, their position in space must be estimated from the data. Depth information can be retrieved when reflection arrival times can be determined from the data. Velocity profiles can be obtained from multiple-offset data common-midpoint gathers, or CMPs, technique coming from seismic refraction [21, 22, 24, 25]. In the CMP configuration, this stacking velocity field is extracted from normal move-out (NMO) velocities, or amplitude move-out (AVO), deduced from standard seismic reflections analysis applied to radar waves. Migration processing is another approach, commonly used, to reconstruct images from a defined velocity, or velocity profile [26]. Grasmueck [27] and Grasmueck et al.[28] studied the 3D-migration for

GPR data defining what requirements and expected resolution function of frequency, for an accurate reconstruction. All these works are the prophets of later GPR applications in civil engineering summarized in following sections.

4. Buildings

There are three major focus areas when GPR is used to inspect buildings. The first is to locate unseen objects and structures for the sake of heritage conservation and construction compliance check. The second is mapping of deterioration and serves as a decision-making tool for preventive/ad-hoc maintenance. The third is assessment of structural damage after natural disasters like flooding, earthquake and landslide. GPR is part of the toolkit that can be deployed to help assess whether buildings are still safe or not after disaster.

The deterioration of buildings is an application area which has many benefits for those occupied buildings. Some assessment methods disrupt the daily activities of the residents and tenants, and therefore not preferred; GPR is minimally intrusive and can be used without major impact on residents and tenants. Maintenance and repair of the buildings are also costly and in many cases, owners tend to act only when damage or failure become visual [29]. Identifying problems early using NDT methods and focusing on areas of minor but long term concern is a better approach. A complete guide of building inspection by NDT is found in Binda et al. [30] and McCann and Forde [31], including impact-echo, acoustic emission, ultrasounds, natural and modal frequency analysis, resistivity, infrared thermography, and GPR. GPR is one of the most popular methods because of the low cost, high resolution, effectiveness and real-time images. Like all NDT methods, GPR is usually best applied in combination with other NDT methods.

Building types can be loosely divided into three groups: cultural heritage buildings, modern buildings and a handful of wooden buildings. Cultural heritage buildings [32-37] are made of masonry, bricks, limestone, sandstone, marble, granite, clay bricks, mudbrick or wood as structural components of arches, columns and vaults support. Modern buildings are often constructed using reinforced concrete; reinforcing is commonly steel and is subject to deterioration [29, 33]. Concrete is strong in compressional loading and weak under tension; steel bars are embedded to take the tensile part of loading. In some construction, the reinforcing may be insufficient, missing entirely (construction fault), or corroded due to constant chemical attack. Use of GPR to assess corrosion in reinforced concrete is discussed later in this paper.

4.1 Cultural Heritage buildings

GPR is very often used to evaluate states of cultural heritage buildings primarily in Europe [38], representative examples are found in Ranalli et al.[32], Leucci et al.[39], Gonzalez-Drigo et al.[34], Hemeda [37], Leucci et al.[40], Pérez-Gracia et al.[41]; Masini et al. [42], Kanli et al.[43]. A summary of the applications is shown in Table 1. Priceless heritage structures such as the precious Basilicas and Cathedrals [32, 44], XIX century factories [34], palaces [37], mediaeval highly modified houses [35]. In cases of modern rehabilitation on heritage buildings, relatively modern structural elements are built on to ancient masonry ones. GPR is extremely useful to help study of the interface between the old and the modern parts of structures constructed at different periods of time [35, 45-47]. Further GPR can be very powerful in identifying older constructions embedded inside walls or buried under the building structures

[35, 48-50]. GPR has also been used to assess the efficacy of cement grouting in historical building [43], as well as in-fill of cracks/voids [51].

4.2 Modern concrete buildings

Many modern buildings are made of reinforced concrete. Most uses of GPR are related to rebar detection and mapping [29, 33, 52]. The applications on modern buildings (slabs, walls and basement floors) are no different from the concrete structures in bridges and roads. Analysis is focused on several directions:

- Object existence like steel bars, pipes, and structural supports and variation of construction materials [33, 34, 53-57];
- Object geometry like radius of steel bars embedded in concrete [55, 58, 59];
- Dampness, void and defects of concrete [52, 60-66], and
- cracks and void detection in concrete [67-69].

In North America, use of GPR has focused primarily on the optimization of cutting of concrete. There is continuous renovation and re-fit of high rise buildings; those constructed from reinforced concrete and containing post tensioning cables can be degraded if the reinforcing and tensioning elements are damaged. In some structures, electrical power and other cabling may be embedded in the concrete. GPR sees its wide-spread use in identifying these embedded elements to minimize structural damage. Best practice guides are promulgated by Concrete Sawing and Drilling Association (CSDA) [70].

In compact Asia cities where most people live in aging high-rise buildings, regular inspections are required, especially in a nondestructive way. This makes GPR a new frontline of applications. An example is the mandatory building inspection scheme (MBIS) in Hong Kong [71], requiring inspection to be done in every building once every ten years. Standards of surface penetrating radar, as one of the listed NDTs in HOKLAS's Supplementary Criteria no.19 [72], regulates a series of requirements, such as qualification of people, on carrying out GPR inspection on concrete buildings. HKCI: TM [73] reports the procedures how a GPR survey should be done on buildings.

4.3 Foundations

In addition to above GPR studies on superstructure, there are also handful of studies about substructure on the interaction between the ground and the foundations of buildings. A few reported examples are

- detection of geological structures under the buildings [74-77],
- location of man-made structures affecting structural safety [34, 49, 78-80], especially on a basement and wall foundation of a Cathedral [81] and museum [82].
- identification of wet ground areas [29, 75] that could cause settlement.

Kannan [83] proposes to make use of GPR in site investigation during site formation stage of building projects, in order to identify areas close to active sinkholes and facilitates structural calculation of foundations. The number of such applications is still scarce because of the difficulty of access with antenna [38]. Borehole GPR [84] offers potential for foundation assessment. Very little use of the method for foundations has been reported in the applied civil literature. Most applications have been for tunnels and geologic assessment.

4.4 Diagnosis due to Mechanical Damages

Natural disasters damage buildings, like earthquakes and landslides. After the disasters, GPR is proved to be a useful tool as part of the solution to support diagnosis in rehabilitation [45, 47, 55], and the possible causes of visible damage [85]. However, such use is still very limited. Retrofit works based on diagnosis of NDT/GPR are rarely carried out and mostly these structures were demolished or patched up without NDT/GPR, even in active earthquake areas like California, New Zealand and Japan.

5. Road, pavement and bridge

5.1 Road pavement

For road pavement inspection, GPR surveys are performed on four types of road pavement: flexible pavements (asphalt layers on sub-base), semi-rigid pavements (asphalt layers on hydraulically bound layers), rigid pavements made of concrete, composite pavements with new asphalt on top and concrete below, and paving block for pedestrian. Unlike other GPR applications where major objects of investigations are embedded objects and hyperbolic reflections are often expected, longitudinal line structures and continuous reflections along the different parts of road structures appear more frequently.

During the 80s, research efforts were mostly devoted to pavement application, using high-frequency air-launched antennas. The FHWA developed one of the first vehicle-mounted GPR system for highway inspections [86]. The French Scientific Network of the Ministry Transport did a similar approach designing a GPR system associated with the corresponding processing software and the frame of a global NDT methodology for pavement thickness measurements [87].

In the 90s, GPR system technologies for road inspection have given rise to faster systems operating at higher frequencies, thanks to the development of semiautomatic processing software [88-92] in response to a demand for high-resolution, time-efficient NDTs and reliability in well-established applications achievable with GPR [93].

The air-launched GPR was perceived to be necessary for road and bridge inspection at highway speeds. Raising GPR antennas off the surface substantially reduces the spatial resolution and subsurface target signal strengths when contrasted with close-ground coupled GPR deployments. In the early 2000's the feasibility deployment of close ground-coupled GPR systems was demonstrated on a number of platforms as exemplified by Leggatt and Annan [94]   Fields results and data analysis benefits of ground-coupled GPR can be found in Diamanti et al [2017] and Redman et al [200?].

In parallel, studies were carried out on the EM characterization of asphalt mixtures, as well as for the estimation of radar velocities [95-97] as for water and void content [19]. During these decades, many articles were devoted to methodological approaches for the evaluation of road structures. From the 80s [86, 87] until the years 2000 [98-102], the road assessment using GPR increased significantly with fast development of the sensor/hardware and software technology.

Concerning the antennas and electronic systems, step-frequency radar were studied during the last 90s because of the advent of better signal-to-noise ratio and higher frequency bands over the impulse systems [103, 104]. With virtual network analyzers and ultra-wide band antennas, one can also survey very-thin asphalt layers as asphalt base and sub-base courses, even if transmit rates were much lower than the impulse commercial systems. Nowadays, array systems are commercially available, with the major advantage to record large amount of data though the major obstacle is the high price compared to impulse radar system.

To date, GPR survey on road inspection is not only about layer thicknesses [105-110] or steel bars [111]. It is also extended to detection of anomalies in centimeter scale, such as cracks [112, 113], voids [114], water infiltration [115], or embedded objects in such small size, as well as structural evaluation [116-118]. A summary of these latest works are shown in Table 2.

5.2 Bridges

GPR survey on bridges is mostly about diagnosis on concrete bridges and masonry arch bridges. Survey is required often when crack, rebar corrosion, water leak are visible. The surveys are carried out either directly from the paved deck or individually on bridge elements like bridge girders, piers or columns. GPR applications on bridges usually concern condition evaluation of a bridge deck, such as cracks, moisture and poor compaction. For crack, an algorithm was presented to the tracking of crack geometry in 3D space [119]. For moisture seepage, attenuated signals are concluded as an indication of deteriorated area although presence of moisture may be mistaken as subsidence [120]. Areas with wide and blurred signal may also indicate area with higher water content and susceptible to damage [121]. GPR was used to assess the condition of two reinforced concrete bridge decks after rehabilitation of cover deteriorated concrete [122].

For compaction, GPR is able to identify areas of improper backfill drainage and a lower degree of compaction [123].

Another important application is about mapping of embedded reinforcement like bars, pre-stressed or post-tensioned tendons, and their ducts [124, 125]. A new approach in Switzerland was developed to provide interpretation in 3D space [124]. With very high frequency antenna (e.g. 2GHz), the rebar locations, cover depths, pre-tensioning and post-tensioning cable trajectories can be mapped successfully [126]. Some new developments of numerical analysis in finite different time domain (FDTD) were concluded to provide good correlations with field data [127, 128] The developed integrated modelling combined photogrammetry, thermography and FDTD algorithms to demonstrate the capabilities and effectiveness of the integrated interpretational tool on bridge inspection [129]. A summary of these latest works are shown in Table 3. Despite the benefits, wide spread adoption has not occurred. Roads departments with research groups have championed use of GPR as a wealth of research publications indicate. Integration of data into pavement management systems (PMS) and building information management (BIM) systems for decision making is still a work-in-progress.

6. Tunnel liners

Different types of tunnel linings can be surveyed by GPR, such as unreinforced concrete, reinforced concrete, shotcrete lining with sprayed concrete and even brick, but not shotcrete containing steel fibres because of random wave scattering. There are two major functions of the survey. The first is the discontinuities/void/grouted space between concrete and rock face or inner lining based on changes of reflection amplitude and estimation of dielectric properties [130-135]. The second is compliance check with designed structural details, for example, rebar cover and location [132, 136], water seepage in fractures [137, 138], thickness of lining [139], homogeneity leading to poor compaction of the lining materials. A table of summary is given in Table 4.

The biggest problem of GPR survey in tunnel is difficult accessibility like traffic disruption, fitting of the antenna systems on tunnel wall or tunnel roofs, and obstruction of cables and conduits running along the tunnel. The antenna systems can be divided into three types, namely single channel air-coupled, single channel ground-coupled, multi-channel array. The survey is performed longitudinally at different clock times, analogous to a drainage pipe survey. It is aided with special frames purposely built and mounted on a vehicle, or with a hand-held antenna if areas of interest is small.

- Single air-coupled system at a range from 1-2GHz [134, 138]: survey is normally carried out longitudinally along the length of the tunnel using air-coupled antenna. Such system gives a shallower inspection range (< 0.5m) but quick inspection in high speed (e.g. about 30 km/h or even faster).
- Single channel ground-coupled system [130-132, 135-137, 139] in a range of 200 to 1500MHz: survey is conducted in a selected zone of interest. The system gives a deeper penetration (in meter scale) and higher spatial resolution but slower inspection speed [140].
- Multi-channel air-coupled and ground coupled antenna array using step frequency continuous wave. These relatively new systems offer flat response of wide GPR frequency bandwidth

(100 to 2000MHz) and therefore may alleviate the major disadvantage of the trade-off between penetration depth and resolution. Its popularity is however still limited because of high price compared to single channel system.

Another major work of tunnel lining survey by GPR is The American SHRP 2 report "*Mapping Voids, Debonding, Delaminations, Moisture, and Other Defects Behind or Within Tunnel Linings* [141]". It studies six different nondestructive testing methods, including ground-couple and air-coupled GPR by comparing deterioration detectability, detection depth and accuracy. Both air-coupled and ground coupled GPR systems were commented favorably. It was concluded that the air coupled GPR can indicate areas of high moisture or low density (high air voids), whilst ground-coupled GPR can possibly detect defects at different cover depths within or just behind the tunnel linings. For any NDT inspection on a tunnel liner, the report recommends to firstly collect and analyze thermal images and air coupled GPR data, followed by selecting areas for detail and further testing by ground coupled GPR and either ultrasonic tomography, ultrasonic echo, or portable seismic property analyzer device. It is clear that GPR plays a central role in this regard. This sequence of work is equally applicable to GPR applications in other types if infrastructures.

7. Geological/Geotechnical Applications

7.1 Landslide, geological faults, erosion and sinkholes

The role of GPR, and other common geophysical methods like shallow seismic, electrical resistivity tomography (ERT), and topographical methods like GPS in geotechnical applications are mostly about validation of the soil and rock profile obtained by point-based borehole log.

Aim of which is to fill in the gap of the soil and rock strata between different boreholes which are normally limited in numbers. A major application is on the slope, where sliding surfaces before and after landslides in natural slope were portrayed to help estimation of the mass of unstable soil [142-144]. Other applications include estimation of internal erosion in embankment dams [145], sinkhole subsidence [146], slope deposits [147], shallow geological fault zones [148, 149] and depth of bedrock [150]. Some examples of these works are given in Table 5.

However, given the capability to delineate soil and rock strata via sampling obtained in borehole record, geophysical methods have so far not been widely considered and used, although its high-resolution of subsurface imaging is recognized [143]. This is probably due to the lack of knowledge about GPR and geophysics in the geotechnical engineering/geological community. Analogous to other applications described in this paper, engineers still incline to believe the soil and rock that they can see visually (borehole log), rather than what they cannot see (geophysical signal).

7.2 Tomographic multi-offset radar and borehole radar

Deployment of GPR in this form commenced in the late 1970's with development of borehole deployed antennas. The biggest driver for borehole GPR was the ability to assess fractured rock mass for suitability for nuclear waste disposal [151, 152]. A more extensive push for hydrogeological applications occurred in the 1990s for smaller scale applications [153].

Tomographic multi-offset's GPR signals are used to image the shallow subsurface in various ways and analysis are very much followed the developments in the seismic field. The most simplistic analysis essentially use simple straight ray approximations to estimate velocity and attenuation. More advanced scalar image solutions use 2D and 3D ray tracing approaches to allow for the impact of velocity variations on the signal paths [154, 155]. Ray-based inversions use only the first-arrival times and first-cycle signal amplitudes [156, 157] and not the full data set acquired. The standard ray tomography can be limited due to other physical responses since the procedure does not take into account diffraction phenomena.

More sophisticated analysis use the full data set to re-construct an image of the subsurface properties. These solutions are referred to as full wave-form inversion approaches. Full-wave form inversions [158-160] have been developed for various applications, and most often are used in relation to water-content estimation in vadose zones. Such inversion procedures require to construct an accurate initial model usually using simpler and faster ray based approaches. The inversion process then iterates the model parameters by comparing the output of a numerical simulation of the full earth and GPR system to the observed data and adjusting the arth parameters to minimize the difference. Finite Difference Time Domain (FDTD)-based simulation software are available to the scientific community, providing GPR modelling tools, like GPR Max [161]. These models include diffraction effects and address guided wave phenomenon [162-166]. These analysis are still in the realm of advanced research and required skilled and experienced users to ensure reliable results.

On the application side, borehole radar is mainly used to characterize different types of fractures and infill within the fractures. Some examples are monitoring steam-enhanced remediation in fracture limestone in a time-lapsed mode [167], study of hydraulic property of the fracture systems with four antenna polarizations [168], depiction of spatial variations in lithology, structures and changing depositional environments [169] and fractured granitic bedrock [170].

All these studies are aided with test wells or borehole log to substantiate the GPR findings. Some examples of these works are given in Table 5.

8. Underground Utilities

The unseen network of underground utilities is a very complex man-made network in any urban city. Ownership and operation of these networks are diversified, that they include high-pressure water supply pipes, gas pipes, power cables, sewers and storm water drainage, telecommunication cables, street lighting and traffic lighting cables. In comparison with the obvious and visible damages in above-ground infrastructures like bridges and roads, the existence and locations of these city vessels and correspondent aging problems remain mysteries, until hazards and problems arise, such as gas explosion, road collapse due to subsurface wash-out, water leakage and seepage to the road surface, etc [171-173]. This section report the previous efforts spent on how the underground utility networks are positioned & mapped, and how their conditions can be assessed by GPR.

8.1 Positioning and mapping

Positioning and mapping of underground utilities in urban area is perhaps the most complicated GPR exercises amongst all types of civil engineering applications. It is because radargram patterns of the urban scenarios of utility orientations, depths, lateral material types and strata are often non-typical compared to other infrastructures like concrete. GPR is often used to positon and map pipes, drums, tanks, cables, burials and underground features [174, 175]. Underground objects of interest in urban area are normally within few metres from the surface which fall well within the GPR survey range [174]. Some successful references summarized in Table 6.

Efficient and large-scale data collection and 3D mapping are particularly important to utility survey. It is because in a 3D scan, continuous reflections resulted from hyperbolas from a series of parallel B-scans can be mapped clearly and be defined as utilities. On the contrary, in a single 2D B-scan traverse, any hyperbolic reflection can be either an utility or some other anomalies with significant dielectric contrast to the host soil, like boulders. 3D scan has been done conventionally by traversing GPR antenna in a X-Y orthogonal grid on ground [12, 14, 176, 177].

On-site systematic gridding process is used because of the time spent on in-situ marking of grid lines. To eliminate use of grids to provide sensors positioning, GPS and Laser tracking theodolites can be used to constantly track the GPR sensor position. While helpful, some navigation or tracking ability is needed to provide the use with feedback that the area has been adequately surveyed and that there are not gaps in the data. All modern GPRs provide the capability to log spatial position from such devices and integrate these features into the data analysis. There are two improvements recently. Firstly, position of antenna can be traced to synchronize grid-free and real-time coordinate/topographic map and downward-looking GPR. The system makes use of real-time kinematic global positioning system (RTK-GPS) and robotic total station by mounting GPS receiver or a 360^0 prism on top of GPR antenna, respectively [178-180]. ‘Downward-looking’ means the GPR data acquisition, processing like migration and imaging with B-scans and C-scans [12, 14, 176, 181]. Secondly, customization of multi-channel GPR system towed by a vehicle enhances the mobility to survey a single traverse covering the width of any road. There are two types of such systems. The first one is step frequency continuous wave (SFCW) making use of common mid-point (CMP) setting and relatively flat response of a large bandwidth compared to pulse radar, such as 3D radar from Norway and Yakumo from Japan [182]. The second one is multi-channel system using ordinary pulse antenna array produced by manufacturers such as IDS, Sensors & Software, GuidelineGeo (formerly MALÅ). Despite these newly evolved instrumentations improve data acquisition efficiency and offer multi-resolution analysis in different depth ranges in 3D space, the complexity of the systems for unskilled users and the high price compared to single channel pulse GPRs are major obstacles to adoption.

The survey results from the GPR mapping undoubtedly yield much larger errors than the above-ground surveying technologies like traversing by total station do. The allowable errors are guided by different standards and guidelines for the purpose of procurement and quality assurance of survey service, as summarized in Table 6. They include ASCE 38-02 [183] from the USA, ICE [184] from the UK, AS 5488-2013 [185] from Australia (2006) and from National Committee for Mapping and Spatial Data (2006) from Malaysia. These standards categorize the utility survey results into four quality levels (QL): QL-A, QL-B, QL-C and QL-D. *QL-A* is the most accurate level because it is an open-up inspection where the utility is exposed after ground truthing by trial pit, followed by *QL-B* making use of two non-invasive geophysical methods: pipe cable locator and/or GPR. *QL-C* relies on observation of ground features (valves, manhole, hydrant, transformer room, etc), while *QL-D* is about desktop study of available records and interview to the local people. QL-A gives the highest accuracy and QL-D gives the lowest. QL-B is about the use of geophysical technique, i.e. pipe cable locator (post-processing not required) and GPR (post-processing required). ICE [184] sub-divides the accuracy into QL-B1P, B2P, B3P ("P" denotes GPR post-processing). Both B1P and B2P allow horizontal and vertical accuracies of survey as a function of detected depth. For B1P, horizontal accuracy is ±150mm or ±15% of detected depth whichever is greater; whilst vertical accuracy is ±15% of detected depth. For B2P, horizontal accuracy is ±250mm or ±40% of detected depth whichever is greater; whilst vertical accuracy is ±40% of detected depth. This depth-dependent accuracy appears to be more realistic in very congested urban areas than other specifications do. It is because it takes into account the facts that accuracy worsens along with increasing depth of utilities, and accuracy of GPR survey should not be comparable to the open-up survey (i.e. QL-A) in the scale of milli-meter because of its nature of indirect measurement. Clients can select the expected level of QL which is closely associated with the cost and expertise or the GPR practitioners.

For indirect measurement in the case of underground utilities, validation in a test site with well-known model answers is essential to train competent operators and analysts, understand the limitation and accuracy of GPR, and establish survey procedures. Some test sites are available worldwide, for example the Mapping the Underworld's test facilities in University of Birmingham [172], mini-city demonstrator Sense-City located at University Paris-Est [186] and also the indoor Underground Utility Survey Lab in The Hong Kong Polytechnic University [187] and Tongji University, Shanghai.

8.2 Condition and hazard assessment due to water-carrying utilities

There is a wide range of condition and hazard assessment of underground utilities like power cable and gas explosion. One of these hazards comes from water-carrying utilities and the associated water seepage, leakage, subsurface soil wash-out and voids that often cause land subsidence and even landslide in hilly city. The root cause is a series of physical and chemical processes triggered by material degradation, or extra external earth load and damage during digging. The assessment of the extent of seepage and pinpointing is therefore required to minimize the damage which is not self-healing and is getting worse over time, as if diagnosis of cancer in early stage is always beneficial to medication and recovery. Diagnosis of water seepage/leakage and void is in fact a process by elimination like forensic science and air crash investigation. It attempts to distinguish and isolate signs of the hazards of various kinds, utilities itself and noise. A review of the underground utility hazards that can be characterized, detected and assessed is given below.

GPR is appropriate to map water seepage, leaks and void because of three reasons [188]. Firstly, it is theoretically promising. Water is the most influential factor to slow down radar wave's traveling velocity, cause attenuation in dielectric construction materials, and absorb the wave's high-frequency component because of dielectric polarization mechanism [21, 97, 189-196]. Secondly, GPR wave travels into the material without sensors' physical contact to the pipes, like valves, as required in other acoustic methods like noise logger and leak noise correlation. Lastly, different depths of water pipe buried in the road or slope can be reached by adopting GPR antenna in different center frequencies. For example, slopes in tens of meter scale can be studied by an antenna of center frequencies ranging from 100 to 500MHz, then seawalls and roads in meter scale are within the frequency range from 400 to 900MHz. Few GPR laboratory experiments and numerical modeling were used to investigate the potential of detection of water leakage [197-206]. These studies proved the possibility of GPR mapping water leakage detection. Accuracy of the results can be enhanced by specific advancing digital signal processing [207] and can be mapped in a 3D space for better visualization [206, 208].

When constant water seepage and leak happen, the underground layers of material experience un-noticed wash-out which forms void space. Identification of such void space requires recognition of local, strong and discontinuous reflections in the C-scans. Then in B-scans, these local, strong and discontinuous reflections shall manifest reverberation/ringing behavior and phase changes relative to direct wave. Also the vertical start of this feature shall not exist at the ground/time zero in the radargrams and shall continue to be attenuated along with depth/time [209, 210]. Criteria of qualifying voids of varied types and combinations are still a matter of research, though the market demand of the technology is growing elsewhere.

To date, the many efforts and literatures focus on individual underground hazards separately but not as a whole, in other words, water seepage/leak and void happen at the same place. It is still not clear how the GPR signals look like when such scenarios in different scales happen under the very complicated underground utility networks. This topic requires a lot of further research, simulation and validation in the lab/field.

9. Concrete properties and corrosion

9.1 Concrete properties

The evolution of GPR applications for concrete structures surveys has grown from geometrical information including reinforcement location, reconstruction of detailed structural elements as well as geometrical pathologies including void, honeycombing and delamination. These recent applications appeared with the evolution of GPR technology with new high-frequency ground-coupled antennas (> 1 GHz). The combination of both hardware and software involved the possibility to map the reinforcement bars and post-tension ducts [211-213]. Moreover, GPR became one major non-destructive testing (NDT) for engineers and structure owners to achieve quantitative engineering properties, such as mechanical strength, porosity, water content or degree of saturation, transport coefficients and chloride ingress, in order to establish precise diagnosis and to implement maintenance program for monitoring the structure conditions during its service life.

Numerous studies focused on relative permittivity for different concrete showing that sensitivity levels were important on large frequency bands (larger than the radar ones) [63, 214-220]. These works have also demonstrated that other parameters could influence the permittivity measurements, such as the type of aggregate, the quantity and nature of finer particles (<80 µm) and the nature of the used cement. They also oriented on the study on GPR measurements, attenuation and travel time, function on water or chloride content [61, 190].

Recent researches tend to combine several NDT using other EM frequency band and mechanical waves to evaluate uncertainties in order to get quantitative data. Several French projects, supported by the National Research Agency, focused on the development of a methodology for the non-destructive evaluation of some indicators related to the durability of concrete by means of a combination of NDT methods. The first project SENSO, tested more than 10 ND techniques on a large configuration of concrete mixtures to study their relative sensitivity to indicators such as: porosity, E-modulus, compressive strength, water content, chloride content and depth of carbonation. From the large database, relationships between NDT measurements and indicators were built. Then, a procedure of data fusion was developed to merge the data collected from several NDT methods [221]. following projects (EVADEOS and ACDC) tend to adapt these calibration relationships from laboratory mixtures, to real structures for one, and to integrate the notion of spatial variability of NDT measurements on a concrete structure to the other one [222]. In that frame, the perspectives of NDT researches, including GPR ones, are oriented to the estimation of gradients of intrusive agents versus depth, and data fusion of complementary NDT presenting similar depth penetration. Studies of other concrete properties like early-age hydration properties and concrete strength/pore system are relatively scarce compared to corrosion. Readers can refer to Van Beek [223], Lai and Tsang [224], Lai et al.[218, 225] for more detail.

9.2 Corrosion

The assessment of concrete properties relies on the inversion of various measured GPR attributes (amplitude, dielectric, velocity, etc) [64, 226-228]. Experimental works, theoretical or empirical models of such process are not as well-established in comparison with those in GPR applications in geophysical research community which have been on-going even before the first GPR conference in 1986. It is probably because civil engineers are less interested in GPR than geophysicists do. This section describes chloride-induced corrosion, as a major part of concrete properties studied by GPR, into two phases: initiation phase and active corrosion phase.

Corrosion of steel bars in concrete is a major threat to reinforced concrete structures, especially in coastal cities and snowy territories with extensive use of de-icing salts. Corrosion is usually characterized into two distinct phases: the corrosion initiation phase and active corrosion propagation phase [229-231] [232-235]. The corrosion initiation phase refers to the intrusion by CO_2, and followed by water and chloride contamination which open the pathway of corrosion development, which is an electro-chemical process. The corrosion propagation phase refers to the depassivation and development of a transition area between concrete and steels, as well as later dissolution of steel into corrosion products that cause cracks, delamination and spalling. Both phases have been studied by GPR in many literatures, and are divided into the initiation phase and corrosion phase in the following two sub-sessions. In these literatures, there exists one paradox which leads to some confusion when GPR is used in large scale mapping of corrosion. The paradox is, whether the practitioners shall look for area of lower intensity or area of high intensity when they co-exist, as a sign of corrosion. To date, scientific community has not yet reached the consensus to conclude an answer, but it seems that such analysis is in fact a running threshold process of intensity (or amplitude of bar reflection) that defines the area of lower intensity as corrosion in initiation phase (Section 1.1.1) and area of higher intensity as active corrosion phase (Section 1.1.2). Still, quantitative thresholds of which are not yet suggested.

- *Initiation phase as a pre-cursor of corrosion*

Intrusion to concrete structure by water and chloride contamination has become an evolving topic of GPR. With increasing water content and chloride content, both direct and reflected waves were attenuated with higher bulk permittivity ε' and conductivity σ [191, 194, 195, 236-242]. The high frequency components revealed in time-frequency domain are also absorbed to shift the center frequency to the lower side [194, 195, 239, 240]. To explain such phenomena, well-established dielectric and volumetric mixing models of soil [10, 243, 244] in early years were used because of the similarity of the three phases (i.e. a solid, gaseous and liquid state) possessed in both porous soil and concrete. The application of these models requires bulk permittivity of concrete which is measured by three ways: (1) time of flight to a known reflector [245], (2) velocity analysis of a hyperbola [245-247], and (3) dielectric contrast based on reflection amplitudes across two distinct dielectric interfaces [245]. Then, the bulk permittivity value can be expressed as a volumetric mixture [248] of individual phases of solid (Calcium silicate hydrates and aggregates), liquid (seawater or fresh water) and gas (air). Bulk permittivity value increases significantly with the large contribution of fresh water (ε_w' = 81; σ = 0.10 – 30 mS/m) and salt water (ε_w'= 70; σ = 400 mS/m) in comparison with the solid part in concrete (ε_s'=5 to 10) and gas/air (ε_a'=1; σ = 0) according to ASTM [245] (2011). To formulate the relationships between chloride content and GPR parameters in a more explicit way, a recent development is the full waveform inversion [64, 228]. In these inverse models, the aforementioned GPR parameters were measured to inversely model the distribution of chloride content within concrete in a more quantitative manner. Water and chloride mapping in concrete structure have been recently applied such as Alani [120]. In near future, these lab- and mathematical-based contributions are expected to blossom in routine mapping contamination of water and chloride in any concrete structures, although it is still not widely accepted by civil engineers to date.

- *Active corrosion phase*

After initiation phase, active corrosion happens and corrosion products (FeO, Fe_2O_3, Fe_3O_4, etc.) around reinforcement bars start to be generated to break the surrounding concrete [234]. The corroded steel bar, along with the generated corrosion products and cracks, yield a wider radiation footprint intercepting the First Fresnel Zone (FFZ) of individual GPR antenna compared to the non-corroded steel bars. The wider FFZ then changes the dielectric contrast across the concrete-steel bar interface, followed by changes of the wave's travel time, amplitude and frequency spectra before and after corrosion. Narayanan et al. [249] started the detection of reinforcement corrosion in concrete with GPR in a field test. Hubbard et al. [250] makes use of accelerated corrosion technique to study the change of GPR signals before and after corrosion. Lai et al. [238] monitored the accelerated corrosion with GPR on one single point continuously for several days. Hong et al. [239, 240, 251] extended Lai's work to 2D measurement in laboratory and investigated the influence of concrete cover depth and rebar size on the accelerated corrosion process studied by GPR. For full-scale evaluation of delamination and cracks caused by corrosion, some examples are Benedetto [119], Tarussov et al.[252], Dinh et al.[253], Martino et al.[254].

10. Method validation, accreditation, specification and procurement

Previous sections summarize successful stories that reach the peer reviewed literature. The case studies of GPR applications in various CE problems focus on success and rarely about failure.. In reality, failure is normal, especially when GPR is repeatedly carried out in commercial contracts. Our combined experiences suggest that failing to meet expectation is far more common than the successes reported. This observation is common for all NDT methods and not restricted to GPR. If one attempts to look beyond the successes to daily engineering practice one finds one or a combination of the following five factors (SWIMS) account for the outcome.

- **S**ervice provider, or simply, the people? Are people skilled, experienced and trained?

- **W**ork procedure? Do the personnel involved plan and follow accepted survey procedure?
- **I**nstrumentation? A wide range of instrumentation is available and is the appropriate device selected? (To some workmen, 'a hammer is a substitute for a screwdriver'. Such an approach is not appropriate with GPR!!)
- **M**aterial on site is inappropriate? In many instances, the environment may not be suitable for using GPR and the method should not be selected. How complex is the infrastructure?
- **S**pecifications in contract? Are requirements of a GPR survey clearly stated? Stating a GPR survey is required but not what's looking for, is meaningless and provides no contractual control or guidance on deliverables.)

The following two steps are suggested as solutions: (1) vendor/method validation and accreditation; (2) procurement and specifications. Validation and accreditation deal with former four factors 'S', 'W', 'I' and M. Procurement and specifications deal with the last 'S'. These two solutions have been adopted in many jurisdictions with varying degrees of success in procurement of engineering services in general.

10.1 Method validation and accreditation

A major reason of the 'X' cases is the lack of well-trained expertise in the service providers 'S", standardized work procedure 'W' and appropriate use/calibration of instrument 'I'. All of which are somehow related to human factors and errors which can be, at least partially solved by method validation and accreditation. Material 'M' in the complex underground also plays a major role in the 'X' case. It is less likely to be human factor but is in fact limitation of the technology in a particular scenario, like soil with high clay content or mapping of objects underneath heavily reinforced concrete. For 'S", 'W', 'I' and 'M' in any CE problems using

GPR, it is important to establish particular validation experiments and dataset for fingerprinting the dataset from site work, and follow the validation procedure below:

1. standardize GPR data acquisition, processing and imaging procedures in particular CE problem (e.g. mapping thickness of tunnel liners, or void under pavement, or corrosion in concrete, etc) through numerical simulation, laboratory scale-down experiment and/or previous ground-truthing field work,
2. carry out numerical modelling/lab experiments, or refer to previous GPR results with ground-truthing to establish validation dataset, and then carry out actual field work,
3. compare the B-scan and C-scan patterns between the validation dataset and field dataset,
4. quantify the effects of different variables (antenna frequencies, depth of target , pipe characteristics and covered material properties) to obtain accuracy using error propagation models required in Guideline of Uncertainty Measurement (GUM) [255],
5. estimate depth ranging limits, lateral and vertical resolution limits as a function of antenna frequencies, target depths, target characteristics and overlaid material properties,
6. suggest what ‘CAN’ and ‘CANNOT’ be done in the particular CE problems.

By going through this process, the service providers should be qualified to apply for accreditation by recognized accredited body. An example in Hong Kong is the implementation of Hong Kong Laboratory Accreditation Scheme (HOKLAS) with enforcement of supplementary criteria [72] on nondestructive inspection and lab validation of concrete structure by surface penetrating radar since 2012. Validation requires a site with known parameters of buried objects like depth, size, materials, etc. Some validation test sites are available worldwide, for example the Mapping the Underworld’s test facilities in University of Birmingham [172], mini-city demonstrator Sense-City located at University Paris-Est [186] and also the indoor Underground Utility Survey Lab in The Hong Kong Polytechnic University [187] and Tongji University, Shanghai.

10.2 Specifications and procurement

A few international organizations or national public institutes promote some guides, standards or recommendations using the GPR technique, some being focused on utility survey. At international level, we can mention the the ASCE (CI/ASCE 38-02) [183] and ASTM international (ASTM D6432-99) [245] in North America, EuroGPR [256] and ITU (L.39) [257] in Europe.

In Europe, EU INSPIRE directive defines data types related to identified utility infrastructure and way of delivery for using by different customers on standardized way. Document "D2.8.III.6 Data Specification on Utility and Government Services – Technical Guidelines [258]" gives guidelines for realization of this task. At a national level in EU, the COST action TU1208 can refer to some standards, like the British PAS-128 [184] completed by the Survey Association from UK which promote a guidance note or "Mapping The Underworld (MTU) [259]" a UK 10-years research program, the italian standard CEI-883 [260], the French standard NF-S70-003-2 [261] completed by the French RST procedure or the AGAP-Qualité guides [262] for geophysical techniques, or the German DGZfP guideline [263]. In parallel, some European projects have worked in the GPR domain, and produced guides – or trainings – such as ORFEUS FP6-Project [264] or Mara Nord Interreg-Project [265].

In addition to specifications, another way of enhancing practitioners' quality of GPR work is to include blind test as part of contractual requirements. Advantage is to avoid incompetent GPR vendors bidding open tender projects requiring GPR at a cheap price and then delivering poor results, a two-envelop system has been developed for underground void survey projects by Highways Department of The HKSAR Government, and executed by The Hong Kong Polytechnic University [266]. The first envelop requires vendors to conduct a blind test with several pre-embedded voids under a reinforced concrete and a pavement. Those who passed the blind test according to a marking scheme modified from the quality level B in PAS-128 [184], proceed to the second envelop stage which compares tender price. The service providers, who tendered the lowest bid price, is awarded the contract for the over Hong Kong's footway for a 18-month term contract.

11. Summary and Conclusion

Our goal has been to provide an overview of GPR and its role in the civil engineering world. The major observations that can be made at this time are as follows.

- GPR is an effective imaging method for many applications
- The technology is still evolving with much future potential
- GPR should be used as one of many parts of the NDT tool box
- Application of specific GPR instruments are appearing to address common basic problems
- Advanced applications need to engagement of a skilled, trained and experienced professional
- Procurement of services needs to be rationalized to avoid inappropriate use

- More training in professional education programs on NDT and GPR is needed

In this paper, we restrict the scope of GPR imaging to real-life applications only whilst other interesting topics like GPR simulation [161], GPR full-waveform inversion [158] and signal processing methods [267] are yet extensively discussed. In fact in the civil engineering and surveying community elsewhere in the world, GPR imaging is still in infant stage. The technology is often regarded as an ad-hoc technology when a difficult problem arises, rather than a recognized technology to be used in areas like structural health monitoring and rehabilitation decision-making. To date, visual inspection via trial pit and extraction of cores are still the most common method to reveal the truth or doubt like 'What is inside?' and 'Is there damage?'. It is probably not because of the unavailability or unpopularity of the GPR imaging technology, but the lack of standardized approach in terms of both technology and procurement of services.

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