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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

Wallace Wai-Lok Lai [a,*], Xavier Dérobert [b], Peter Annan [c]

[a] Department of Land Surveying and Geo-informatics, The Hong Kong Polytechnic University, Hong Kong
[b] Université Bretagne-Loire, IFSTTAR, Centre de Nantes, 44 344, Bouguenais, France
[c] Sensors & Software Inc, Canada

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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.

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 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 10–5000 MHz range. For this reason, GPR instruments are referred to as ultra-wide band (UWB) radio wave devices. The GPR signals are electromagnetic 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 centimeters depending on the GPR system bandwidth. This resolution scale is a good match for the scale of mapping needed of infrastructure assessment.

The advent of GPR started in the field of geo-science after mid-1950s, and gradually adopted in civil engineering since mid-1990s. After 2000,

* Corresponding author.
E-mail address: wllai@polyu.edu.hk (W. Wai-Lok Lai).

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technological advancements and tremendous improvements of digital computation power have led to the blossoming of 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, interpretation of both 2D and 3D are still highly subjective and depend greatly on the user experience and understanding to extract diagnostic information,. 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 [289] 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 Archeological & 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 a 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 10–10,000 10-5000 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 operations in the 10–100 MHz range are suitable for imaging deep foundations on the tens of meter scale; GPR's in the 100–1000 MHz 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 defined by variations in the electric and magnetic properties of the material. Soils, rocks, concrete and biomass which often form construction materials are generally considered lossy dielectric media normally composed of a mix of components. For example, a soil contains 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 that 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 give 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 a 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 were 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 10–100 MHz frequency range and the water relaxation at 10 GHz. There are few polarization relaxations in the 100–2000 MHz range where the predominant use of GPR occurs. In this frequency range, velocity and attenuation dispersion are comparatively small resulting in 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 usefulness 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 identical.

Over the last several decades, GPR has been widely studied and enhanced for numerous sub-surface geophysical applications with link to civil engineering; this section can only provide an overview of the some 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 geophysical studies investigate the electrical properties of various sedimentary soils, mainly clay, silty soils, rocks, as a function of water content that shows 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. 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 came 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 or common-midpoint (CMP), technique originated 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 commonly used approach 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 the sake of an accurate image 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 toolkits that can be deployed to help assess whether buildings are still safe or not after natural 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 its high resolution, effectiveness and availability of 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; rebar is commonly steel and is subject to deterioration [29,33]. Concrete is strong in compressional loading and weak under tension; rebars are embedded to take the tensile part of loading. In some construction, the rebars 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. [39,40], Gonzalez-Drigo et al. [34], Hemeda [37], 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 ancient masonry ones. GPR is extremely useful to help

Table 1
Some examples of applications of GPR on BUILDINGS.

References	Antenna frequency	City	Building types	Subject of investigation	3D*	Major findings and remarks
Kanli et al. (2015) [43]	400 and 900 MHz	Sopron, Hungary	fire tower	Voids and cracks before and after cement injection	No	Reflections from the fractured and porous zones are weakened or lost. Cores are available to validate the signal.
Orlando and Slob (2009) [78]	2 GHz	Chieti, Italy	historical building	Floor stability affected by a landslide	Yes	Utility, Iron bar and some cracks can be detected from parallel broadside profiles after 3D single component algorithm. The variation of images is caused by season changes. Electromagnetic wave velocity in summer is higher than in winter.
Xie et al. (2013) [69]	–	–	–	RC structure voids	No	support vector machine model is developed to automatically identify voids with high accuracy. Multiple waves caused by steel bars contribute to void positioning.
Barraca et al. (2016) [57]	500 and 800 MHz, 1.6 GHz	Ilhavo, Portugal	Rehabilitation building	Local Geological Condition; unknown infrastructure location; removed walls; moisture and fracturing investigation	No	GPR is capable of investigateing local geological conditions, maping infrastructure, locating altered elements, as well as understanding changes in construction materials and pathologies and fracturing. Interpretation on different brick requires more experiments.
Panisova et al. (2016) [80]	500 MHz	Svaty Jur, Slovakia	church	Subsurface anthropogenic structure; wall foundation	Yes	Four medieval crypts are delineated; west wall foundation in 1/3 of the nave, and northwards oriented. Spatial model integrated in to the visualization helps to yield more realistic images of the subsurface features.
Rucka et al. (2016) [50]	2 GHz	Gdansk, Poland	tower of church	Boundary between masonry and reinforced concrete	No	The diffraction-refraction scattering at the boundary are identified with the developed procedure. A series of formulation are derived to describe the refracted hyperbolic diffraction curve. The point of the refraction indicates the boundary between media.
Pérez-Gracia et al. (2013) [41]	900 MHz and 1.5 GHz	Palma, Spain	cathedral	Inner structure of walls, damaged zones	No	Columns are built with mass if ashlars, with no important voids or irregular materials. A few centimeters' irregularities present in walls' inner side; buttresses are made by two stones walls with irregular materials filled. The inner stone contact is close to the surface when the profile is on a stones junction
Ranalli et al. (2004) [32]	600 and 1600 MHz	L'Auila, Italy	church	Wall thickness, internal masonry structure and detachments or cracks' locations	No	Wall thickness vary fairly; elongated stones, detachments and cracks in façade and ashlar facing are found. Wall thickness is a significant finding in seismic modelling.
García García et al. (2007) [45]	400 and 900 MHz, 1.5 GHz	Valencia, Spain	church	Location of tombs	Yes	Mausoleums are solid, and anomaliesare found in the crypt floor profiles. 3D cut-out display was suggested. Spectral analysis is a suitable tool for object recognition
Pérez-Gracia et al. (2008) [46]	500 and 900 MHz	Valencia, Spain	theatre	Point of contact between before and after modification	No	The velocity obtained in the older part of the theatre are lower than expected because the materials are wet. Sharp variation in wave velocity occurs at the point of contact between different materials
González-Drigo et al. (2008) [34]	400 and 900 MHz	Barcelona, Spain	historical building	Structural strength of the modified columns and load-bearing walls	No	Local weakness of the floor, original power lines and water conduction are detected. Structural elements can be identified by analyzing wave velocities. Reflections of cluttered material around may lead to misinterpretation of the data.
Kilic (2015) [65]	2 GHz	Urla, Turkey	primary school	Cavities and water ingress hidden within a structure	Yes	Voids, change of materials and pipes are evident in radargram. Integrated approach can detect both visible and hidden structural condition.
Kim et al. (2014) [66]	1200 MHz	Korea	prototype containment building	Concrete structure	No	Reliable images corresponding to the reinforced steel bars and defects such as void, but void and metal sheath pipes beneath the reinforcing steel bars could not be detected by GPR because of electromagnetic shielding. Pre-test helps in select best array of antenna concerning polarization.
Moropoulou et al. (2013) [51]	1.6 GHz	–	cultural heritage	Preservation state of structural system and mosaics	No	Cracks are detected penetrate into the complete thickness of the ashlars; pulse penetrate into the masonry and detects. Pay attention on void spaces when deciding large portion of the mosaic.
Barrile and Pucinotti (2005) [33]	1600 MHz	–	civil building	Location of steel reinforcement; seismic vulnerability of the building.	No	Aspect on the structural elements investigate are important. Steel bars are located. Radar wave would be sharply reflected at the interface between rebar and concrete.

3D* means either cube view or slice scan.

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 useful 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 beams 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 widespread 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 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 semi-automatic 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, in contrast with 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 discussed by Leggatt and Annan [94] Fields results and data analysis benefits of ground-coupled GPR can be found in [231].

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 methodology 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 larger 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.

Table 2
Some examples of applications of GPR on ROAD PAVEMENT.

References	Antenna frequency	City	Road types	Subject of investigation	3D*	Major findings and remarks
Solla et al. (2013) [106]	1 GHz	–	Asphalt pavement	Uncertainty in thickness of pavement	No	The influence of repeatability and reproducibility of GPR are important interpreter in expended uncertainty evaluation. The correction obtained from calibrated data are closer to real value. The correction and expended uncertainty has no dependence on layer thickness.
Varela-González et al. (2014) [107]	2 GHz	–	Concrete pavement	Pavement thickness	No	A developed semi-automatic program with an intuitive interface functions efficiently. Capability of processing large data at a time can led to faster diagnostics.
Stryk et al. (2013) [111]	1.6 GHz, 2.6 GHz	–	Concrete pavement	Dowel and tie bar position	No	Accuracy reaches 1 cm in terms of rebar location; the horizontal direction is influenced by the distance of dowels and tie bars in between themselves. Vertical distance depends on velocity measurements in such materials.
Diamanti and Redman (2012) [112]	250 and 1000 MHz	–	pavement	Cracks	No	Stronger diffractions are detected in 250 MHz, when 1000 MHz describe more crack characteristics. 2D & 3D numerical modelling depicted the crack filling materials and crack aperture, as well as asphalt conductivity. When modelling, only relative amplitude comparisons between model and field data are possible.
Li et al. (2016) [114]	1.5 GHz	–	Reinforced concrete pavement	Pavement thickness and air voids	No	A shorter wavelength range is proposed in dynamic models and P-wave velocity when estimate the thickness. Air voids can affect the estimation of wave velocity. The impact echo methods is proved to be accurate in estimating the thickness of concrete pavements.
Solla et al. (2014) [113]	1 GHz	Ourense, Spain	Asphalt pavement	cracks	No	GPR is suitable for identifying the origins of the crack in depth, but no relationship is found in measuring amplitude and crack depth. Thermographic study provides supplement info in crack depth and size.
Leng and Al-Qadi (2014) [268]	2 GHz	–	Pavement	Dielectric constant and thickness	No	The extended common mid point (CMP) is developed, but its performance of is not as good as surface reflection, because of the sampling rate limitation and the possible overlap of GPR signal reflection. Higher sampling rate may result in better accuracy in CMP measurement.
Zhao et al. (2015) [109]	2.0 GHz	Chicago, USA	Asphalt pavement	Thin layer thickness	No	Regularized deconvolution increases the resolution of overlapped pulse, and the thickness calculation error is small.
Zhao and Al-Qadi (2016) [108]	200 MHz–3 GHz	–	Asphalt pavement	Pavement thickness	Yes	With extended common mid point (XCMP) method and 3D GPR, and a numerical solving technique based on the least squares principle, asphalt layer thickness of a large coverage area are measured in fast speed. The XCMP method can provide more accurate dielectric constant values without calibration.
Xu et al. (2014) [117]	200 and 400 MHz	Beijing, China	highway	Roadbed damage	No	The developed novel 60 channel GPR joints positioning with video system, improves survey efficiency. Loose roadbed is indicated by the clutter and layer discontinuities.
Sun et al. (2017) [118]	0.5–6.5 GHz: 0.1 GHz step	–	highway	Roadway structure evaluation	No	A modified MUSIC algorithm for time delay estimation; interface roughness is estimated by using Maximum Likelihood Method for time delay. When rough road surface is investigated, the scattering mode can be taken into consideration.
Lorenzo et al. (2011) [116]	500, 800 and 1000 MHz	–	highway	Roadbed survey	No	The designed trailer functions properly with normal vehicle speed. With non-metallic chassis and rolling elements, the interference in the GPR signal form elements are minimized.
Faucharda et al. (2003) [105]	2 and 1.5 GHz	–	highway	Asphalt layer thickness	No	Results of the cores, CMP and permittivity measurements are compared. After numerical reconstruction, measurements of the first two layers thickness are satisfactory. If GPR system can work at high moving speed, traffic obstruction can be avoided.
Venmans et al. (2016) [115]	900 MHz	The Netherlands	Asphalt pavement	Monitor moisture condition in subgrade and road base	No	The GPR detects that ground water table is at a greater depth up to 1.35 m. Repeating and averageing measurements are applied to remove reflectors constant in time such as pavement layers.
Pitoňák and Filipovsky (2016) [110]	2 GHz and 400 MHz	Ziarnad Hronom, Slovakia	motorway	Layer thickness and pavement roughness	No	The GPR results show that ¼ layers are built by more than 10% thinner than designed structure. The antenna survey speed should be reduced for the sake of a closer contact to the surface of pavement.

*3D means either cube view or slice scan.

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 novel approach in Switzerland was developed to provide interpretation in 3D space [124]. With very high frequency antenna (e.g. 2 GHz), the rebar locations, cover depths, pre-tensioning and post-tensioning cable trajectories can be mapped [126]. Some new developments of numerical analysis in finite different time domain (FDTD) were concluded to provide good correlations with field data [127,128]. Integrated modelling with combination of photogrammetry, thermography and FDTD algorithms was developed on bridge inspection [129]. A summary of these latest works is shown in Table 3. Despite the availability of well-developed methodology, use of GPR is still in an ad-hoc based but not regular-based. Integration of data into pavement management systems (PMS) and building information modelling (BIM) systems for decision-making purpose is still yet to be developed.

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

Table 3
Some examples of applications of GPR on BRIDGES.

References	Antenna frequency	City	Bridge types	Subject of investigations	3D*	Major findings and remarks
Alani et al. (2013) [120]	2 GHz	Edinburgh and Kent, England	Road bridge	Damage rebar and moisture ingress	Yes	Two similar cases are tested. Higher signal attenuation indicates deteriorated area; presence of moisture may be mistaken as subsidence. When surveying bridge, yielding a significant quantity of data is important.
Varnavina et al. (2015) [122]	1.5 GHz	–	Concrete bridge	The process of deterioration of surface concrete	No	A linear relation between GPR data and depth is established. The map of reinforcing steel, different weather conditions caused varying linear slope and intercepts. GPR data are based on the reflection amplitudes from the top transverse layer of reinforcement and do not present the condition below.
Kosno et al. (2016) [123]	900 MHz	–	Bridge deck	Flexible soil-steel structure testing	No	Improper backfill drainage and a lower degree of compaction are detected. GPR can be used as an efficient tool for final inspection and identification of poor workmanship.
Benedetto (2013) [119]	2 GHz	–	Concrete bridges	Tracking cracks, corrosion associated with reinforcing bars.	Yes	A new algorithm is presented in automatic tracking cracks in the bridge decks. It features at capacity of following the exact geometry of the crack in 3D space. 3D imaging is applied to detect voids, cracks or buried objects. And numerical approach indicates the noneligible increase of the signal amplitude produced by defects.
Hugenschmidt and Mastrangelo (2006) [124]	1.2 GHz	–	Bridge planned to demolition	Inspection of concrete bridges	Yes	EMPA approach are carried out and gap in the result for the problems in sectionsare caused by resolution problems and interpretation uncertainties. 3D inspection provides a detail insight into concrete structures. No deeper rebar was found by the mobile acquisition unit.
Diamanti et al. (2008) [127]	1.5 GHz	University of Salford	Arch bridge	Ring separation in brick masonry	No	A method of introducing subgrids into FDTD numerical analysis is proposed, and it results in good correlations. Hairline delamination between the mortar and brick masonry cannot be detected.
Solla et al. (2011) [128]	250 and 500 MHz	Lugo, Spain	Arch bridge	Evaluation of roman masonry	No	With FDTD simulation on the external geometric measures of the structure, the interpretation indicates the ancient profile of the bridge and subsoil zones. Different signal response observed could be an indication of different stonework and fill materials with the bridge.
Solla et al. (2016) [129]	500 MHz	Lubian, Spain	Historical bridges	Evaluation of a bridge suffered different restorations.	No	The developed integrated modelling that combines photogrammetry, thermography and FDTD algorithms demonstrates the capabilities of the effective interpretational tool.
Hasan and Yazdani (2014) [121]	1.6 GHz and 2.6 MHz	Roanoke, US	Concrete bridge	Explore inadequate concrete covers	No	Wider and blurry hyperbola shape might indicate the area with more water content. It may not be true to assume that the dielectric constant is uniform in a newly placed concrete.
Kosno et al. (2016) [123]	2 GHz	Trynka river, Grudziadz, Poland	Pre-tensioned Concrete Bridge Beams and precast girders	Rebar location and cover depths and post-tensioning cable trajectories and 'T' bridge girders	No	The rebar location, cover depths, pre-tensioning and post-tensioning cable trajectories are measured. GPR is proven as a good quality control method.

*3D means either cube view or slice scan.

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 tunnels 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 in a range from 1 to 2 GHz [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 (<0.5 m) 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 200–1500 MHz: survey is conducted in a selected zone of

Table 4
Some examples of applications of GPR on TUNNEL LINERS.

References	Antenna frequency	City	Tunnel types	Subject of investigation	3D*	Major findings and Remarks
Lalagüe et al. (2016) [134]	400 MHz; 1.5, 2.6, 1 and 2 GHz; 100 MHz–3 GHz	Vestfold, Norway	Cave-in penetrated the concrete lining	Void behind the inner lining; rockfall from the tunnel roof	Yes	The Step frequency GPR is suitable for measuring distance between inside and rock surface. Ground-coupled GPR is the best for detecting loose rocks. Tunnel liner should be scanned immediately after tunnel construction.
López-Rodríguez et al. (2016) [269]	100 MHz	Teotihuacan, Mexico	Tunnel beneath the temple	Archeological subsurface strata	No	Multi-cross wavelet (MCM) reflectes the mixed limestone and clay compound; while Fourier multi-cross function (FMC) analysis suggestes tunnel and chamber are filled with similar materials. Applying FMC and MCW algorithm helps determine the similarities of the tunnel and chamber filling periods
Zhang et al. (2010) [131]	250 and 500 MHz; 1 GHz	Shanghai, China	Metro line	Grout thickness behind the lining segments	No	500 MHz is the most suitable frequency. The result can be improved if the dielectric constant of the grout at exact dates corresponding to the field test are measured. Predetermination of travel time through the line segments and dielectric parameters contribute to accurate measurement.
Cardarelli et al. (2003) [130]	200, 450 and 225 MHz	Apennines, Italy	Catchment tunnel	Elastic and discontinuities in the rock; identify loosened zone; quality of contact between concrete and rock	No	Limestone is highly fractured and filled with air; loosened band found from radar coincide with seismic refraction; non-fractured area are found. Plotting different data sets on same scale produces reasonable data correlation and integration.
Hugenschmidt and Kalogeropoulos (2009) [136]	400, 900 and 1500 MHz	Geneva, Switzerland	motorway	Retaining wall	Yes	The use of 400 MHz GPR does not penetrate deeper because of the abundance of rebar; the fusion of datasets obtained from different orientations reduce the directionality of radar data. It is not possible to decide whether the anomalous reflectors are related to rock anchors or not, based on radar data alone.
Li et al. (2011) [139]	900 MHz	Long Hai Tunnel, China	tunnel	Liner thickness	No	Lining interfaces are automatically identified by peak value criterion method. Compared to artificial recognition, automatic recognition offers coarseness of lining layer.
Yu et al. (2016) [135]	800 MHz	Nanchang, China	Metro	Grouting layer thickness; presence and distribution of any damage	No	Thickness is measured 30 cm; damages like low density, voids, crack and fissure were observed. Comparison of the field data with the models makes an accurate interpretation.
Xiang et al. (2013) [132]	500 MHz	Fujian, China	highway	Locate rebar; estimate lining thickness ad damage	No	Smaller rebar interval than requirements is found; hyperbolic reflection indicates voids and cracks. 2D-FDTD simulation and symmetry-based algorithm locates true rebar positions.
Li et al. (2010) [137]	31–36 MHz	Qiyunshan, Jinping and Qingdao, China	tunnel	Water inrush prediction; groundwater in fractures;	Yes	The developed prediction system combines tunnel seismic prediction (TSP), GPR and transient electromagnetic method (TEM). Faults and fractures can be predicted by combining seismic and radar method; while groundwater predicted by combining radar and transient electromagnetic methods. Combined methods can maximize the advantages and avoid disadvantages.
Zan et al. (2016) [138]	500 kHz 6 Channels; cf: 300 MHz	Baozi-Zhongwei line and Xiangfan-Chongqing line	railway	Regular inspection of railway tunnel: deformation, liner thickness	No	A developed train-mounted GPR system produces fast survey on defect integrity and deformation. Scanning rate should be high enough to match the normal train speed.

*3D means either cube view or slice scan.

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 (100–2000 MHz) 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) 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 unknown 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 motivation for borehole GPR was the ability to assess fractured rock mass for suitability for nuclear waste disposal [151,152]. A more extensive hydrogeological application 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 follows the similar developments in the seismic field. The most simplistic analysis essentially uses 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] but not the full acquired data set. 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 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 is still in the realm of advanced research, requires skilled and experienced users to produce 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. Unlike other infrastructures where ownership and operation are well-defined, those in underground utility networks are diversified and ill-defined in many ways. These networks include high-pressure water supply pipes, gas pipes, power cables, sewers and storm water drainage, telecommunication cables, street lighting and traffic lighting cables, etc. 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 in most cities. Their importance would not be obvious 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 position and map underground features like pipes, cables, drums, tanks and burials [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 are 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,

Table 5
Some examples of applications of GPR on GEOTECHNICS.

References	Antenna frequency	City	Geotechnical types	Defect types	3D*	Major findings and Remarks
Sass et al. (2008) [142]	25, 50 and 100 MHz	Swabian, Germany	landslide	Marls and limestones thickness; internal structure	No	The base of the slide is visible in cross-profile as a brunch of rough surface parallel reflections. GPR info from a depth more than 10 m is handicapped by the strong damping of loamy sediments and by overhead reflections in woody terrain.
Carpentier et al. (2012) [143]	100 and 250 MHz	Urseren Valley, Switzerland	landslide	Soil composition and geometry of interfered	No	Three major soil-interfaces in shallow landslides are imaged. A conceptual model of local shallow landslide are derived. The schist layer, clary layer and fractured bedrock are observed showing up as major dielectric contrasts.
Hu and Shan (2015) [144]	40 MHz	China	landslide	Sliding surface	No	The radar wave shows strong reflection at the position of the sliding surface, where the amplitude of the radar wave exhibits a sudden increase. Sudden change and abnormal radar wave reflection can be used as a basis for diagnose.
Carlsten et al. (1995) [145]	120 and 500 MHz	Sweden	erosion	Detect location of core crest	No	Difference between water content in the core and that in the upper filter resulted in reflections. Determined velocity improves accuracy.
Avila-Olivera and Garduño-Monroy (2008) [148]	50 MHz	Michoacan, Mexico	Geological faults	Subsidence-creep-fault	No	With common-offset single-fold profiling, a fault plane dividing two blocks is visualized. The assessment of the "net throw" is quantitative when derive from a radargram.
Gómez-Ortiz and Martín-Crespo (2012) [146]	200 and 400 MHz	Segovia, Spain	Subsidence of sinkhole	Assess occurrences and detect cavities	No	Locally discontinuous warped reflections indicates sinkhole outcroppings, as well as carbonate dissolution processes. Intense reflections correspond to small cavities in terrain.
Gerber et al. (2007) [147]	–	Germany	slope	Detect slope deposits	No	400 MHz is the most suitable frequency. The most important effect of the substrates is the difference in water content of bordering layers. Water content dependent relative permittivities and reflection coefficients calculated may be used for further GPR measurements. Water content dependent relative permittivities and reflection coefficients calculated may be used for further GPR measurements.
Beben et al. (2013) [150]	200 and 800 MHz	–	River bank	Determine bedrock depth	No	The bedrock course is determined. Weathered shale turning into the bedrock of shale is noticed below the backfill. The proper selection of the EM wave velocities is one of the important tasks of GPR survey.
McClymont et al. (2010) [149]	100 and 200 MHz	South Island, New Zealand	Alpine fault zone	How displacements are accommodated	Yes	By identifying distinct reflection patterns, subsurface extent of two main structural faces is determined. And two regions of warped strata are interpreted. GPR surveys have the potential to help identify sites that are amenable to geomorphic reconstruction.
Mansour et al. (2014) [270]	30–100 MHz	Mirror Lake, USA; Lake Nasser, Egypt	Hydraulic property	Delineate the characteristics of subsurface fractures	No	Higher frequency components are less sensitive in evaluation of the small fracture surface roughness variation; hence the depolarization effect of the electromagnetic waves gets stronger compared to that obtained with low frequencies. The result of the first site can be used to evaluate that of the second site.
Grégoire et al. (2006) [271]	100 MHz	Maine, USA	Fractured limestone	Monitor the injection of steam in fractured rocks	No	Variation in fracture fluid electrical conductivity can have a significant impact on EM wave attenuation and fracture reflectivity; and a reflection amplitude analysis method is developed to delineate fractures. Both EM wave velocity and attenuation depth change substantially when the electrical conductivity of the limestone matrix increase because of heating.
Nielsen et al. (2009) [272]	100 MHz	Rømø Wadden Sea barrier island	Sea barrier island	Constrain spatial variations in lithology, structures and changing depositional environments	No	Two significant reflections with good continuity is observed. Strong lateral variations in amplitude characteristics illustrate that the lower clay layer was not throughout the study area. GPR wave velocity may change obviously with depth, and correct velocity analysis of coincident CMP data is essential for a good migration and depth-conversion result.
Serzu et al. (2004) [273]	60 and 22 MHz	Manitoba, Canada	Bedrock	Detect and characterize fractures and fracture zones	No	Water-saturated discrete fractures, fractures zones and radar velocity were determined. Radar tomography interpretations show good correlation with the geological model. Lower velocities correlated to more fractured, highly transmissive rock, while higher velocities are found in less fractured rock.

*3D means either cube view or slice scan.

Table 6
Some examples of applications of GPR on UNDERGROUND UTILITIES.

References	Antenna frequency	City	Utility types	Subject of investigation	3D*	Major findings and Remarks
Jeng and Chen (2012) [209]	200 and 800 MHz	Taipei, Taiwan	Subsurface utilities	Potential collapse	Yes	Ensemble empirical mode decomposition (EEMD) reduces exponential decay and meaning full images show disturbance signals which indicates possible destruct. Set control study in field help demonstrate the efficiency and quality.
Li et al. (2015) [274]	800 MHz	–	utility	Struck in underground utility, model and communicate uncertainties.	No	The hybrid 3G system achieved horizontal/vertical accuracy of 100 mm/300 mm. The positional error increases with the buried depth, which raise the importance of awareness in spatial inaccuracy and uncertainties in utility location data.
Metwaly (2015) [275]	400 MHz	Holy Mecca, Saudi Arabia	utility	Locate subsurface utilities.	No	Reflected hyperbola classify sewage and PVC pipes; flood drain shafts and material interface are detected by reflected signals.
Sagnard et al. (2016) [186]	300, 500, 900 MHz and 1.5 GHz	Paris, France	utility	Benchmarks in imaging various dielectric pipes and blades buried at various depth.	Yes	900 MHz frequency survey provides better images of subsurface; spatial sampling with half wavelength is suggested; TM polarization is not suitable for high impedance dielectric pipe. By interpretation and comparison of the Bscanare characterized the dielectric properties of the soil layers.
Jaw and Hashim (2013) [276]	250 and 700 MHz	Persiaran Kewajipan, Malaysia	utility	Location accuracy of buried pipes	No	Multiple closed objects cannot be imaged by perpendicular- to-pipe scanning technique. Along-pipe-scan got level A of quality precision. Accuracy is evaluated by *t*-test and RMSE.
Lester and Bernold (2007) [277]	500 MHz	Raleigh, USA	Water pipe	Performance of TIWPD filtering	Yes	Translation Invariant Wavelet Packet Detection (TIWPD) filter improves characterization capability of GPR; discrete wave analysis enables "real-time". TIWPD filter identified terracotta pipes, showing potential in locating large-metallic drainage pipes.
Ayala-Cabrera et al. (2011) [278]	1.5 GHz	Dry soil under controlled conditions	Plastic pipe	Generation tools to aid inspection and identify buried plastic pipes	No	The developed workflow: intensive matrix manipulation-multi agent system: achieves automatic plastic pipe location. Demand of highly skilled GPR prospection operators can be eliminated by automatic process
Porsani et al. (2012) [279]	200 MHz	Sao Paulo City, Brazil	Utilities under Subway	Locate utility, shape and orientation	Yes	Targets like pipes are characterized by hyperbolic reflections of strong amplitude; circular anomalies indicate possible former structure. Combination with boreholes and opening trenches is important.
Al-Nuaimy et al. (2000) [280]	–	–	Buried utilities and solid objects	Develop a system for automatic detection	No	The system: neural network classifier-pattern recognition stage by Hough transform, returnes high resolution image in efficient time. Edge detection after recognition leads to significant reduction in the amount of data.
Khan et al. (2010) [281]	–	–	Landmines and utilities	Automatic detection of landmines and underground utilities	No	The developed cepstral approach method applies neural network to train 1-D signals and DCT performs the most appropriate for feature extraction. Cepstral feature is pre-extract from a group of images.
Ismail et al. (2013) [282]	250 MHz	Penang, Malaysia	Pipes, manhole trench, and cable	8 parallel traverses at a spacing 2 m	No	Location and orientation of utilities at a depth <2.5 m is successful.
Cheng et al. (2013) [177]	100, 270 and 400 MHz	Hong Kong	Drains, water mains, electricity cables	132 traverses in 4 sites	No	Location of utilities is successful. Results from 100 MHz antenna were not useful
Eide and Hjelmstad (2002) [283]	10 MHz–3.4 GHz step frequency	Trondheim, Norway	pipes, cables and old tramlines	1 m wide antenna array with 31 pairs of Tx/Rx bow-tie antenna	Yes	Location of utilities is successful. The antenna array was mounted on a trailer that is pulled by a vehicle
Grivas (2006) [284]	NA	New York, USA	All types of utilities	14 multi-channel system	Yes	Location of utilities in is successful 3D, giving very efficient and superior 3D images
Van Schoor and Colvin (2009) [285]	500 MHz	Pretoria, South Africa	Utilities and tree roots	51 traverses at a length 12 m and spacing 0.5 m	No	–
Metwaly (2015) [275]	400 MHz	Holy Mecca city	All types of utilities	13 traverses along two ring roads	No	Location of utilities is successful
Birken and Oristaglio (2014) [174] Oristaglio et al. (2001) [286]	200 MHz	Bronx, New York	All types of utilities	NA	Yes	Location of utilities is successful

*3D means either cube view or slice scan.

like boulders. 3D scan has been done conventionally by traversing GPR antenna in a X-Y orthogonal grid on ground [12,14,176,177].

To eliminate the use of rectangular grids for positioning of GPR antenna, GPS and laser tracking theodolites can be used to constantly track the position of GPR antenna. 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 no 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° 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, Guideline Geo (formerly MALÅ). Despite these newly evolved instrumentations improve efficiency of data acquisition 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 of wide applications.

The survey results of 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

Table 7
Comparison of horizontal and vertical accuracy requirements in different specifications.

Quality Level	Sub-QL	Survey Method	Accuracy	
			Horizontal	Vertical
QL-D	D	Review records, Interview	/	/
	D	Records, Cursory Site Inspection, Anecdotal Evidence	Indicative Location	/
	D	Search/collect/analyze records	/	/
	QL-D	Desktop utility records search	/	/
QL-C	C	Survey and plot visible above-ground utility features	/	/
	C	Surface Feature Correlation and Interpretation, Site survey of visible evidence	Approximate Location	/
	C	Survey surface appurtenances of utilities	/	/
	QL-C	Site reconnaissance	/	/
QL-B	B	Geophysical Methods	Tolerance defined by the project	/
	B	Survey and Trace	±300mm	±500mm
	B	Geophysical Methods	/	/
	QL-B4	Detection	/	/
	QL-B3		±500mm	/
	QL-B3P *			
	QL-B2		±250mm or ±40% of detected depth whichever is greater	±40% of detected depth
	QL-B2P *			
	QL-B1		±150mm or ±15% of detected depth whichever is greater	±15% of detected depth
	QL-B1P *			
QL-A	A	Actual exposure and subsequent measurement of subsurface utilities	Applicable horizontal survey and mapping accuracy as defined or expected by the project owner	±15mm
	A	Potholing	±50mm	±50mm
	A	Excavate test holes	±100mm	±100mm
	QL-A	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

* “P” means post-processing of signals which means GPR in the specification

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 ±150 mm or ±15% of detected depth whichever is greater; whilst vertical accuracy is ±15% of detected depth. For B2P, horizontal accuracy is ±250 mm 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 (Tables 7–8.3).

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, water is the most influential factor to slow down radar wave's traveling velocity, causing 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 500 MHz, then seawalls and roads in meter scale are within the frequency range from 400 to 900 MHz. Few GPR laboratory experiments and numerical modelling were used to investigate the potential of detection of water leakage [197–206]. These studies proved the

Table 8.1
Centroid, spread and cover depth of air-filled voids in a blind test template.

	Centroid of Void/meter			Maximum Spread of Void/meter	Cover Depth of Void/meter
	Northing	Easting	Confidence rating*		
Void 1	818616.397	836517.544	50	0.45	0.348
Void 2	818617.459	836519.054	100	0.4	0.050
Void 3	-	-	100	-	-

* See Tables 8.1–8.3.

Table 8.2
Confidence rating in a blind test template [287].

0	25	50	75	100
The answer is a blind guess.	It seems that the answer is correct.	The answer may possibly be correct.	We are pretty sure on the answer but with some doubt.	We have no doubt on the answer.

Table 8.3
Marking scheme in a blind test template of underground void survey modified from ICE-PAS 128 (2014) [184].

Parameters of interest	**Score**			
	Full score is only given when confidence rating=75 or 100, otherwise half score is given even the accuracy is reached	**Half score**	**No score**	**Score deduction by 4 marks only when confidence rating=75 or 100**
Position of centroid of void	Position error is <=50% of the actual cover depth of void, or within 0.6 m to the centroid of void, whichever is greater.	Position error is >50% and within 100% of the actual cover depth of void, or within 1.0 m to the centroid of void, whichever is greater.	Position error is >100% of the actual cover depth of void, or beyond 1.0 m from the centroid of void, whichever is greater.	Position error >150% of the actual cover depth of void, or beyond 1.5 m from the centroid of void, whichever is greater
Maximum horizontal spreading of void*	Spread error is within 40% of the actual maximum void spread, or within 0.5 m, whichever is greater	Spread error is >40% and within 80% of the actual maximum void spread, or within 1.0 m, whichever is greater	Spread error is >80% of the actual maximum void spread, or beyond 1.0 m, whichever is greater	N/A
Cover depth of void*	Cover depth error is <=20% of the actual void depth	Cover depth error is >20% and within 40% of the actual void depth	Cover depth error is >40% of the actual void depth	N/A

* This item was only marked when full score or half score is given in the position of centroid of void.

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, many efforts and literatures focus on the aforementioned underground hazards separately but not as a whole. It is still not clear how complex the GPR signals are, when such mixed scenarios in different scales happen under the very complicated underground utility networks. This topic requires a lot of further research, simulation and validation works 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 rebar 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 rebars 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 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 higher frequency bands (exceeding the GPR normal bandwidth) [63,214–220]. These works suggested that concrete constituents and mix could also influence the permittivity measurements, such as the type of aggregate, the quantity and nature of finer particles (<80 μm) and the cement origin. 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 NDT methodology for the evaluation of durability indicators 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, 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 framework, 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 used to signal processing 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 and area of higher intensity as active corrosion phase. Still, quantitative thresholds of which are not yet suggested.

9.2.1. 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 ($\varepsilon_w' = 81$; $\sigma = 0.10$–30 mS/m) and salt water ($\varepsilon_w' = 70$; $\sigma = 400$ mS/m) in comparison with the solid part in concrete ($\varepsilon_s' = 5$–10) and gas/air ($\varepsilon_a' = 1$; $\sigma = 0$) according to ASTM [245]. 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.

9.2.2. Active corrosion phase

After initiation phase, active corrosion happens and corrosion products (FeO, Fe_2O_3, Fe_3O_4, etc.) around rebars 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 rebar 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 incompatible with the method selected? 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 being looked 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 procurement procedure and tender specification improvement. 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 'failure' 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 civil engineering 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 a particular civil engineering 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, target characteristics and covered material properties) to estimate accuracies using error propagation models such as 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 unprecedented 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], Nondestructive testing lab in Federal Institute of Materials Research and Testing(BAM), Berlin, Germany [288], 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 guidelines, standards or recommendations using the GPR technique, some being focused on utility survey. At international level, few of those are 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 qualify the blind test in the first envelop and tendered the lowest bid price, is awarded the contract for the over Hong Kong's footway for a 18-month term contract. This arrangement attempts to select the most competent service provider and at the same time, taking care of the fairness of cost component in an open tender system.

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 require engagement of 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 decision-making in rehabilitation scheme. 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. But given the large increase of wider audience, we stay positive to the development, and we do expect a much wider use of this technology in future decades.

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