ARTICLE IN PRESS

NDT&E International xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

A review of Ground Penetrating Radar application in civil engineering: A 30-year journey from Locating and Testing to Imaging and Diagnosis

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ARTICLE INFO

Keyword:
Ground Penetrating Radar (GPR)

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, technological advancements and tremendous improve-

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http://dx.doi.org/10.1016/j.ndteint.2017.04.002
Received 12 January 2017; Received in revised form 6 April 2017; Accepted 17 April 2017

ments 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