PROJECT 4.4
"APPLICATIONS OF GPR IN ASSOCIATION WITH OTHER NON-DESTRUCTIVE TESTING METHODS IN BUILDING ASSESSMENT AND IN GEOLOGICAL/GEOTECHNICAL TASKS"
STATE OF THE ART AND OPEN ISSUES

Klisthenis Dimitriadis[(1)], Vega Perez-Gracia[(2)]

[(1)] GEOSERVICE, Geological & Geophysical Consultants
35, Lykaiou St., 114 76 Athens, Greece
workst@geoservice.gr

[(2)] Department of strength of materials and structures, EUETIB (CEIB), Universitat Politècnica de Catalunya (BarcelonaTech), c/Urgell 187, 08036 Barcelona, Spain
vega.perez@upc.edu

Abstract

Geophysics is the study of the earth's interior, using measurements based on physics principles. A part of this, geophysics is also used to explore the interior of construction materials of buildings and Monuments. The major advantage of this science is its absolute non-destructive character. However, despite geophysics exist since the beginning of the 19th century the Ground Penetrating Radar (GPR) method is recently introduced in this domain, counting almost 50 years of active contribution. During these years, GPR was proved very effective in the building assessment. In the field of geotechnical tasks and especially in geological tasks, its efficiency was limited and strongly dependent on the site conditions, mostly due to its limited in-depth penetration and relative target discrimination. Future research must be oriented to the improvement of these two major milestones, mostly into the antennas design and related instruments electronics design.

I. INTRODUCTION

The GPR method was invented during the Vietnam War from the Americans, as a tool to locate the mines below the ground surface. Even today, the method is still used for the same purpose, apart from all the other areas of application. The principle of GPR is to send with an emitter antenna, very short electromagnetic pulses through the ground or the structure. Those pulses propagate towards all directions (or in the half-space downward only, if the antenna is shielded) and are reflected when they meet interfaces between media of different electromagnetic properties. A receiver antenna measures the amplitude of the signal over time (Fig. 1). On the resulting scan, both the direct wave and the waves reflected on the different interface scan are observed. This method allows detecting voids, layers interfaces, humid zones and material modifications. In reality, the GPR method is closely related with the classic seismic reflection method. The difference in these methods is the type of wave used to travel in the media. In the case of the seismic reflection method, the wave is a brief acoustic pulse where in the case of GPR it is an electromagnetic pulse (Dirac). Based on the above concept, the applications of GPR extend from the allocation of small cracks into the concrete or the stone, up to the deep mapping of lake bottoms, or even glaciers thickness of several hundreds of meters.

II. The GPR in concrete and buildings evaluation

The reinforced concrete (RC) is the modern building material in our world today and its degradation with time, the corrosion of its reinforcing bars creates conditions that require a periodic control of its critical properties. For this reason, assessing concrete properties and durability indicators (strength, porosity, moisture content, etc.) using NDT methods can play an important role in the process of RC structures management before any expensive maintenance is undertaken. However, the main problem is the limitation of only one NDT technique to evaluate one concrete property. For instance, GPR technology is sensitive to water saturation but also slightly sensitive to porosity [1], ultrasound is able to evaluate the modulus of elasticity but it is also sensitive to moisture and density, and so on. For these reasons, some researchers have proposed combining several techniques for concrete strength evaluation or for detection and visualization in concrete structures, or the combination of several NDT parameters obtained with the same technique [2] in an attempt to confirm the diagnosis or to reduce the measurement noise. This original approach, which consists in combining NDT data, is promising but only if the additional cost is balanced by an enhancement of the diagnosis quality. In the context of concrete evaluation of existing structures as building, GPR can be used as a complementary method for the rapid evaluation of moisture which could lead to correction of the effect of moisture on seismic methods. The term “seismic” includes all methods based on acoustic pulses, ranging from ultrasonic to subsonic spectra, i.e., ambient vibrations, Impact-echo and down to seismic refraction tomography profiling). Seismic data provide valuable and complementary information like dynamics modulus and vibration modes, highly related to damages and structural solutions. Masonry structures are also frequently evaluated by means of GPR in combination with other techniques, as i.e., in historical buildings. In this case, non-destructive analysis is a helpful process to assess their conditions. Notwithstanding, some problems appear in the case of these special constructions: the high variability of the materials and structural elements (frequently poorly documented) and their irregular surfaces. Recently, the question of detection limits of commercial antennas was studied. It is proved that for layers thinner than $\lambda/11$(for an error inferior to 10 %), the reflection coefficient still depends linearly on the thickness to wavelength ratio [3]. It is also proved that layers with a thickness inferior to $\lambda/100$ (about 1.3 mm here) could be visible with GPR. By this method, the amplitude reflected by a thin layer can be estimated. The layer will then be visible if this reflected amplitude, after subtraction of the losses (including the intrinsic and geometric attenuations), is superior to the signal noise.

III. The GPR in the geotechnical sector

In the geotechnical sector and a part of road infrastructures assessment, GPR is used mostly in foundation studies and sometimes in cuts & retaining structures studies for the assessment of the geometry of the shallow geological layers. During the last years, GPR was frequently used in studies of wind generators foundations. Usually, these constructions are installed at very high altitudes, top of mountain areas, where the rock is strongly weathered and very often hides large cavities or entire caves. The depth of investigation must be in the range of 7-8 m and GPR becomes a good method for a fast subsurface 3D mapping. A significant constraint is always the superficial “skin” layer that in many times is presented as a very conductive clay layer. In these cases, GPR cannot be applied and the use of electrical 2D profiling is inevitable. In almost all cases of wind generators foundations, a skin layer exists, either as one clay layer, or as one thin gravel layer. The gravel layer imposes problems in GPR application on site, mostly from the irregular scattering of the pulse into the gravel voids. This problem can be avoided by using lower antenna frequencies but this reduces the target resolution. Other applications in the geotechnical sector include mapping of utilities or unknown infrastructures like pipe networks, hidden reservoirs and other. Due to low depth of these features, the GPR can be used alone, although is advised to be used with another geophysical method in a parallel sense to reduce uncertainty. A typical example is shown in the (Fig. 2), where the existence of one old subsurface drainage system below an ancient prehistoric grave (Tholos Acharnon, Greece) was identified with GPR and mapped with accuracy with 2D electrical imaging. However, the major problem of GPR is also noticed here. Is it obvious that features with high resistivity (hot red areas: drainage system) are easily mapped with GPR (see at the offsets of 0 to 8 m of the electrical profile). In contrary, a thin low resistivity layer (see at the offset of 15 to 18 m – thin blue region with resistivity down to 15 Ohm*m) makes almost invisible the second feature (rectangular tank) in the GPR corresponding section. Other applications are related to subsurface imaging below the foundations of Monuments. Damages in these structures could be due to foundations problems or shallow geological features. Usually antennas from 400 to 100 MHz are utilized. Seismic methods use to be the most applied as complementary survey, and in shallow profiles, seismic shear-wave velocity layering correlates well with GPR layers interfaces. In many cases resistivity methods could provide also layers stratification to correlate with GPR interfaces. An example is shown in (Fig. 3), where results from the study of the ground under the Cathedral of Mallorca [4] are presented. Two different geological zones produce different images in GPR diagrams and in resistivity images, being also different the seismic wave velocities associated to the layers in both areas. It is usual to combine geophysical methods to different techniques or evaluations, like finite elements models or other, photogrammetry, laser scanning or other optic or topographic measurements. In Greece, GPR method is widely applied in geotechnical issues regarding ancient monuments. In the retaining wall of the sanctuary of Oropos, the GPR method was used for the assessment of the soil as well as the construction details of the wall [5]. The width of the wall has been defined, using a 800 MHz antenna, providing valuable information for the geometry and therefore the load bearing capacity of the structure.

IV. The GPR in geological applications

In the area of geological applications, the classic geophysical methods like seismic refraction and electrical resistivity profiling dominate today in the private sector services. In addition to these methods, Low Frequency Electromagnetics (VLF) in combination with very old geophysical practices like the Spontaneous Potential method, or Micro-gravimetry fill the modern services palette of today's modern geophysical services providers. The GPR method is not widely used today in the geological services sector. This is mostly due to two major disadvantages of the GPR, the penetration depth and the difficulty of application on true site conditions. An additional disadvantage of GPR, in relation to other geophysical prospecting methods is the inability to penetrate into the water saturated zone. The groundwater level presents for GPR an absolute reflector of all the transmitted energy so there is no possibility to map any kind of geological or anthropogenic features below the groundwater level.

In general, GPR is considered a valuable method for shallow geophysical investigations, as archaeology, where all targets are covered from a shallow earth skin layer and the resistivity contrast between the environment (usually sediments) and the building material (usually rocks) is high. In this case, GPR is very effective but still as long as the site and soil conditions permit the application of the method. In a wide number of cases, GPR is used as supporting survey, being other geophysical methods the main exploration procedure. Perhaps the exception is in archaeological sites first evaluations, where 3D GPR imaging provides valuable information about the shapes and structures existing in the site, and use to be applied as main study before excavations. Working with GPR to support other geophysical methods in exploration geology means to operate at frequencies of 100 MHz and below, up to 25 MHz. Using antennas in these frequencies, penetration depth can reach sometimes to 40 m in very resistive formations like limestone or granite. In these cases it is possible to map with accuracy the fault zones and shallow strata with one outstanding resolution, as long as there is no earth skin cover to attenuate the signal. Fault mapping is one critical geological application in the initial phase of tunnel design works and assessment. It is evident that faults affect strongly the tunnels construction and especially when a significant overburden exists, a fault may induce inflows into the tunnel front, slowing down the entire project and imposing a significant increase in construction costs to stabilize the front. In this specific case, the GPR method when applied in low frequency antennas can be very helpful. Significant correlation of GPR (at 25 MHz range) with Very Low Frequency Electromagnetics (VLF) has been proven. This is due to the fact that the fault zones identified from very low frequency EM currents are wide enough in space (20 – 30 m fractured zones) to be allocated with these antenna wavelengths. In addition, due to their high resistivity contrast with the hosting environment (high resistive rocks) together with their irregular geometry and step inclination, these zones are easily identified with GPR. The Rough Terrain Concept antenna of MALA GEOSCIENCE at 25 MHz frequency performs very well in these application areas. In resistive environments, the 250 MHz ground coupled antennas can reach depths of 6–7 m maximum, being still in the range of some geological – geotechnical applications such as the mapping of cavities, fractures or voids. In this sector, the GPR is used in a complementary sense with the geophysical 2D resistivity imaging method. In fact, the depth of penetration of 6 m is enriched from the resistivity profiling and the accuracy on the discontinuities of rock is enriched from the GPR profiling. This complementary use of these two different methods has been proved very effective on site and provides accurate results. In tunneling assessment during the construction phase, GPR survey is also possible, mainly using borehole antennas in the tunnel front when potential faults and cracks could exist. However, in many cases, non-directional antennas are used in borehole applications. In this case, the main difficulty is to define the azimuth of the different targets, and three or more boreholes are needed in order to place accurately the anomaly. Notwithstanding, faults and non-stable areas could be well defined. Borehole GPR is also applied to study buildings foundations before tunneling in dense areas (e.g., in cities) where constructions are poorly documented. Detection of paleo-channels and streams is other possible GPR application, used for different studies. Microzonation is used to define soil predominant period values, usually associated to extended areas. GPR could be a useful tool to determine shallow geological features and to define different ground areas, previously to the vibration measures. These zones could be determined by the existence of paleochannels or streams in quaternary materials, because soil seismic response change due to the presence of these geological structures.

Plus and Cons of GPR in geological applications

A part of the penetration problem, the field irregular topography imposes always a problem in the application of GPR, especially with the ground coupled antennas. This is a serious application problem because even with a topography correction the ground roughness induces a very high noise level in the data. Clearing the paths prior to measurements is impossible for geological applications. With the RTA 25 MHz unshielded antenna, MALA has done one important step toward this direction. However, unshielded antennas are not the best tool when operating outwards due to the high amount of unwanted surface reflections (trees, buildings etc). The need for a new type of antenna strongly exists in these areas. This antenna must be of an air coupled type, shielded in order to send all the energy downwards and in low frequency ranges, to be able to penetrate enough into the subsurface. The first requirement (air coupled type) is the most important for geological applications, due to the fact that an air coupled antenna will be easily carried above the ground with a constant motion or alternatively with a mechanism, avoids also the vegetation or other obstacles.

V. FIGURES

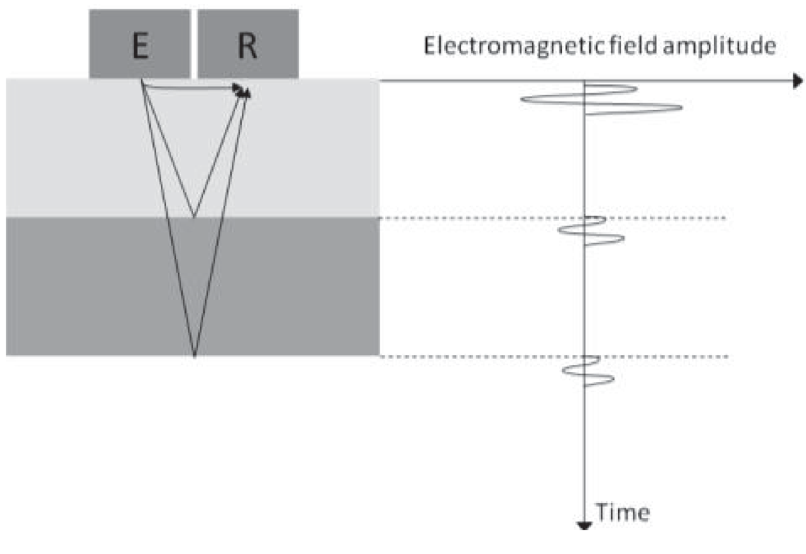

FIG. 1 – Simplified GPR signal measured on a two layers structure.

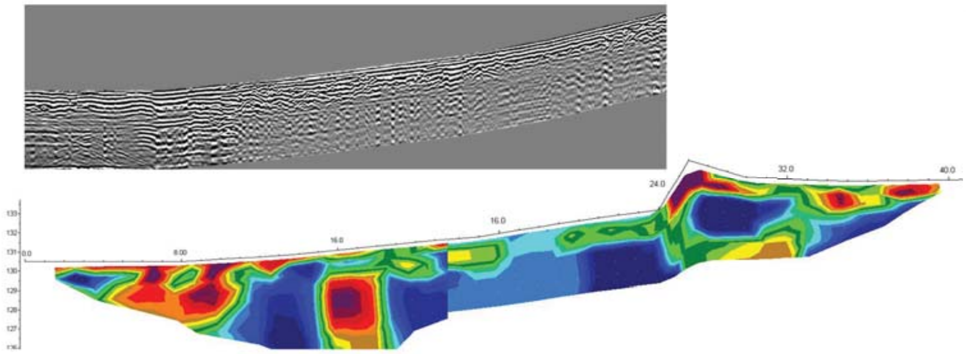

FIG. 2 – GPR and 2D electrical imaging profiles of one old drainage system below an ancient grave (Tholos Acharnon).

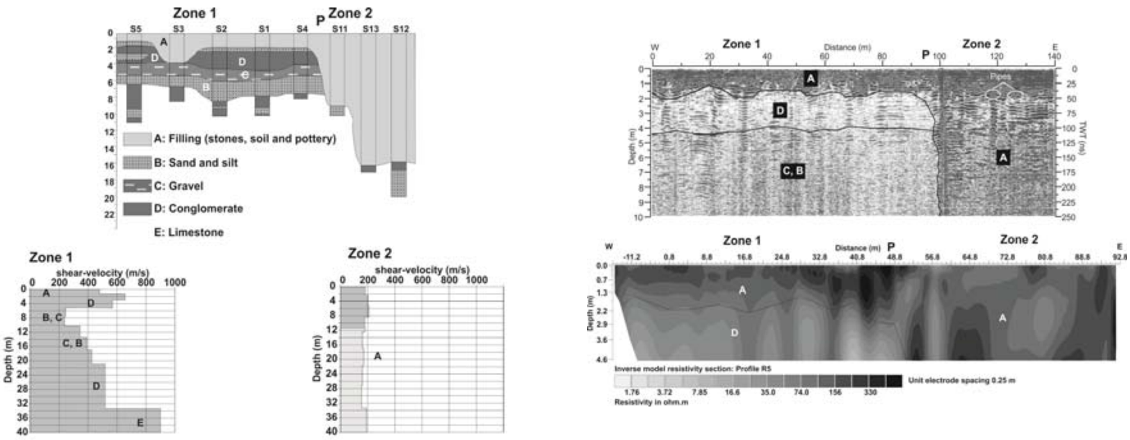

FIG. 3 – GPR data compared to resistivity imaging, ReMi (seismic shear-wave velocity) and strata from borehole data, in the evaluation of the ground under the Cathedral of Mallorca (from Pérez-Gracia et *al.* [9]).

VI. CONCLUSION

Major milestones for the GPR method in geological and geotechnical sectors remain the penetration depth that is seriously lower to other geophysical methods and the easiness of the application of the method in the rough field conditions. Although the problem of penetration is unsolvable so far as it depends on the signal energy, efforts must be oriented to increase the penetration of the signal. Air coupled antennas in the low frequency range are also a promising orientation but so far, only a few are present in the active market. Another issue is the improvement of the borehole GPR antennas especially in positioning and especially in azimuth. Horizontal Directional Drilling technologies are very elaborated in these fields and possibly a combination with the these technologies (beacons) could solve the position problem. In the buildings assessment in contrary, the GPR method is much more elaborated and marketed especially from his fastness and easiness on site. This is a promising sector, taking into account that parallel methods are elaborated in the same time, like for example the multi-spectral image analysis of concrete [6] and other.

Acknowledgement

The authors acknowledge the COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar", supporting this work.

References

[1] Sbartaï ZM, Laurens S, Balayssac JP, Ballivy G, Arliguie G. Effect of concrete moisture on radar signal amplitude. ACI Mater 2006;419:103–426.

[2] Sbartaï ZM, Laurens S, Viriyametanont K, Balayssac JP, Arliguie J. Nondestructive evaluation of concrete physical condition using radar and artificial neural networks. Constr Build Mater 2009;837:845.

[3] A. Van der Wielen1*, L. Courard2 and F. Nguyen2 (Static Detection of Thin Layers into Concrete with Ground Penetrating Radar). GPR, Vol. 18, No. 3/4, 247–254 (2012)

[4] V. Perez-Gracia, J.O. Caselles, J. Clapes, R. Osorio, G. Martvnez, J.A. Canas, "Non-destructive analysis in cultural heritage buildings: Evaluating the Mallorca cathedral supporting structures", Journal of Archaeological Science 36 (2009) 1289–1299.

[5] Kl. Dimitriadis, A. Androvitsanea (Geophysical and geotechnical analysis of the retaining wall of the Archaeological site of Amphiareion, Kalamos). Report submitted to the Greek Ministry of Culture (December 2012).

[6] J. Valenηa, L.M.S. Gonηalves, E. Jïlio (Damage assessment on concrete surfaces using multi-spectral image analysis, Construction and Building Materials 40 (2013) 971–981.