

Ground Penetrating Radar for archaeological investigations and cultural-heritage diagnostics: Research activities in the COST Action TU1208

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Abstract – This contribution aims to offer an overview on the most interesting activities fulfilled by Members of the COST (European Cooperation in Science and Technology) Action TU1208 “Civil Engineering Applications of Ground-Penetrating Radar,” concerning the use of ground-penetrating radar (GPR) and complementary non-destructive testing (NDT) techniques in archaeology and for cultural-heritage diagnostics. In most cases, archaeology exploits the great potential offered by the GPR technique in limited areas and without complementing it with other NDT approaches, whereas the combined application of multiple high-resolution prospecting methods at the scale of landscapes and their integrated interpretation are still uncommon. Therefore, this contribution starts with a mention to two large-scale GPR inspections, where extraordinary results were obtained. The paper continues with a review of a selection of cutting-edge case studies where GPR, eventually combined with other NDT approaches, was used to study archaeological sites and other structures of high historical value realised in different ages, ranging from the 13th century BC to the modernist period and including tombs, monuments, cathedrals, buildings, bridges and statues.

I. INTRODUCTION

Ground-penetrating radar (GPR) is a safe, effective and non-destructive (NDT) technique that uses electromagnetic waves to provide high-resolution images of the sub-surface, or to assess the inner status of a structure [1, 2].

In archaeological studies, digitization and management of cultural-heritage, GPR is especially useful. It can be successfully employed to discover and map buried archae-

ological artifacts, to inspect ancient buildings, bridges, columns and statues, to investigate frescoes, mosaics and decorations; and to study the internal conditions of several other objects of historical value.

The use of GPR is not limited to the investigation of man-made structures. Indeed, this technique can also be exploited for the inspection of natural structures of geological, biological or landscape-conservation value, which are part of our cultural heritage as well, such as trunks and roots of veteran trees, glaciers, caverns, fossil beds, sand dunes, and more.

COST (European Cooperation in Science and Technology) is the longest-running European framework supporting cooperation among scientists and researchers across Europe and beyond. Founded in 1971, it is currently integrated in the Horizon2020 programme. COST does not fund research itself, but provides support for networking activities carried out within Actions: these are bottom-up science and technology networks, with a four-year duration, which are open to all categories of partners (researchers and experts from universities, public and private research institutions, non-governmental organisations, industry, and small and medium-sized enterprises).

The Action TU1208 started in April 2013 and is ending in October 2017. It involves 150 partner Institutes from 28 COST Countries (Austria, Belgium, Croatia, Czech Republic, Denmark, Estonia, Finland, France, former Yugoslav Republic of Macedonia, Germany, Greece, Ireland, Latvia, Malta, The Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, and The United Kingdom), a COST Cooperating State (Israel), 6 COST Near Neighbour Countries (Albania, Armenia, Egypt, Jordan, Russia, Ukraine), and 6 COST International Partner Countries (Australia,

Colombia, Hong Kong Special Administrative Region of the People's Republic of China, The Philippines, Rwanda, U.S.A.). The scientific structure of the Action TU1208 includes four Working Groups (WGs). WG1 focuses on the design of novel GPR instrumentation. WG2 deals with the development of guidelines for the surveying of transport infrastructures and buildings, and for the sensing of underground utilities and voids. WG3 studies electromagnetic forward and inverse methods for the solution of near-field scattering problems by buried structures and data-processing techniques. WG4 is concerned with applications of GPR outside from the civil-engineering area and integration of GPR with other technologies. The use of GPR for archaeological prospection and cultural-heritage diagnostics is studied in WG4.

The purpose of this paper is to offer a short overview on the most interesting activities fulfilled by TU1208 Members concerning the use of GPR and complementary NDT methods in archaeology and cultural-heritage diagnostics.

II. ARCHAEOLOGICAL INVESTIGATIONS

Archaeological features and materials are hidden beneath the surface as a consequence of natural effects and human activity over the years.

In the field of archaeological prospecting, a wider application of GPR and complementary non-invasive investigation techniques needs to be fostered, for the identification and visualization of buried archaeological heritage. Archaeological excavation provides unparalleled information about the past, but is a costly process and, by its very nature, is destructive to the site under study. By contrast, subsurface mapping methods can cover wide areas while leaving the site undisturbed. A couple of decades ago, these methods represented a means of finding sites; nowadays, they also provide detailed information about the site and offer a good overview of past human activity and buried structures of historical interest in a surveyed area. Considering the methodological and technological development that archaeological fieldwork has undergone during the past century, we can expect that future archaeologists will have at their disposal scientific possibilities that today are not even imaginable. Thus, important sites should be currently studied as much as possible by using non-invasive approaches and be kept intact for future generations; when digging is deemed useful or necessary, subsurface mapping methods represent powerful tools to be exploited in order to select the highest-potential areas for targeted scientific excavations.

GPR archaeological surveys started as small-scale approaches to detect buried features and identify their main geometric and physical properties. In the last ten years, thanks to technological advancements of GPR, the sensitivity and resolution of this method has increased and

data can be acquired at a much faster speed. Therefore, instead of mapping the remains of individual constructions, it is now possible to explore entire ancient towns and landscapes, covering several square kilometres rather than hectares. This implies that a higher number of formerly unknown and otherwise invisible structures can be discovered; more complete information about a region of historical interest can be collected; it is possible to fill the gap between different buildings or ruins and study their relations; and the significance of a monument can be appreciated much better, because a deep understanding of the landscape around it can be achieved.

Two large-scale investigations were carried out by scientists involved in TU1208, namely in Carnuntum (Austria) and Stonehenge (United Kingdom).

The site of the Roman town of Carnuntum is located about 30 km south-east of Vienna and is mostly covered with agriculturally-used fields. It extends over an area of about 10 square kilometres. The whole area of Carnuntum, comprising a civil town, as well as a military camp and settlement, has been mapped in great detail. Magnetometer systems for large-scale prospection have been employed; earth-resistance measurements have been performed and remote-sensing techniques have been used; the subsurface has been imaged with different single-channel and multi-channel GPR systems. Extraordinary results have been obtained, including the unique discovery of the school of gladiators. Such structure was first mapped with a single channel 900 MHz GPR system, and subsequently investigated in great detail using a multichannel 400 MHz array with only 8 cm crossline spacing. More information is available at <http://lbi-archpro.org/cs/carnuntum/>.

As is well known, Stonehenge occupies one of the richest archaeological landscapes in the world, where archaeological and antiquarian research has been intensively carried out over centuries. The aim of the *Stonehenge Hidden Landscape Project* was to address gaps in our knowledge and advance the understanding of the Stonehenge landscape, by conducting a cutting-edge geophysical- and remote-sensing survey on an unprecedented scale. Hundreds of new features were discovered and a detailed archaeological digital map of the Stonehenge landscape was produced. More information about the project and achieved results can be found at <http://lbi-archpro.org/cs/stonehenge/>.

As far as the use of GPR for the investigation of individual archaeological sites is concerned, among the most interesting studies carried out by TU1208 Members is the inspection of the Tholos Acharnon Tomb, near Athens (Greece). This is an ancient Mycenaean monument dating back to the 13th century BC [3], having a circular shape and made with irregular stones. The curved rough surfaces of the tomb represented a challenge for data acquisition and interpretation. The main objectives of the survey were

to identify hidden elements inside the walls, study the arrangement of stones, and detect damaged zones. During data acquisition a laser scan was used, in order to record the position and path of each radargram. The most interesting outcome of the investigation was the three-dimensional description of the internal structure of the tomb walls; furthermore, zones where the GPR signal was highly attenuated were identified, probably due to a high salt content.

Another interesting study was carried out by Action Members from the Universite catholique de Louvain (Belgium), in the Villa Gallo-Romaine de Mageroy, near Habay-La-Vieille (Belgium). The villa's origins date back to the first century AD and the site has been under investigations since more than 20 years by the Groupe d'Archeologie de Habay. By using GPR, new Mageroy secrets have been revealed: a new edifice of the villa and a drainage network have been unveiled. More information about the project are at <http://sites.uclouvain.be/gprlouvain/mageroy.html>.

The Carthusian monastery of Bourfontaine, north-east of Paris (France), was established between 1323 and 1325 and hosted 24 brothers living in separate cells. Bourfontaine survives today as a monumental ruin and a working farm. Here, Action Members carried out a GPR survey over a rectangular area of 30 m per 50 m [4]. Time slices at different depths gave clear evidence of buried architectural structures. The performed superposition of the surveyed zone with the extrapolated plan was particularly remarkable, allowing for a clear identification of three monastic cells, as well as of foundations of the great cloister alley. Based on the GPR results, targeted excavations were planned and carried out.

It is interesting to underline the huge importance, in all GPR areas of application considered in this and in the following Sections, of modelling methods for the electromagnetic simulation of complex scenarios. Radargrams usually do not have a direct resemblance to the subsurface or to the structures over which GPR is used. Various factors, including the innate design of the survey equipment and the complexity of electromagnetic propagation in the scenario, can disguise complex structures recorded on GPR profiles. Radar data need to be properly processed and interpreted, in order to obtain geometrical and physical information about the surveyed structure or area. In that respect, the simulation of GPR scenarios is of primary importance in understanding how target structures get translated into radargrams. Electromagnetic models significantly aid in the interpretation of complex data sets, facilitate object localisation, shape-reconstruction and estimation of geophysical parameters; they help to find out unknown details about the investigated structure or subsurface. Additionally, an electromagnetic simulator can be employed before a survey, to support the choice of the most proper GPR equipment. TU1208 Members have developed

and released interesting open source or freeware tools for the electromagnetic modelling of GPR scenarios, the most significant being a new version of the software *gprMax*, which implements the finite-difference time-domain technique [5].

III. ASSESSMENT OF MONUMENTS, HISTORICAL BUILDINGS, BRIDGES AND STATUES

TU1208 Members performed a number of cutting-edge GPR investigations on historical buildings and bridges. Moreover, a few studies regarded the assessment of ancient statues.

Interesting results were obtained in St. Mary's Cathedral of Mallorca (Spain), a Catalan Gothic-style building dating back to the 14th century [6]. Using GPR and seismic tomography, the activities aimed at assessing the conditions of a series of columns. Images of their internal structure were obtained and cracks not visible from the outside were identified. Other columns were assessed in the 20th-century Hospital de la Santa Creu i Sant Pau, in Barcelona (Spain) [7]. Those studies are of particular interest because the application of GPR to vertical structural elements is still rather uncommon. Electromagnetic models of columns were also implemented, by using the open-source simulator *gprMax* [5], and very good agreement between experimental and synthetic data was obtained [8]). It is worth mentioning that GPR technology and the methodology developed for column assessment also has application in the field of tree trunk investigation [9].

In 2015, the Action organised a training school in Cracow (Poland); an insight into the challenges, advantages and potential of GPR prospection in historical cities was presented. Experimental sessions were held in the famous St. Leonard's Crypt, under the Wawel Cathedral of St. Stanislaus BM and St. Wenceslaus M, built in the years 1090-1117. The floor of the crypt was surveyed, in order to obtain an image of the tomb of Bishop Maurus, verify whether further cavities were present, and collect information about the subsurface of the crypt. GPR scans were taken on a 20 cm x 20 cm grid. Subsequently, an interesting area of smaller extent was chosen, where further data were collected on a 10 cm x 10 cm grid. The main finding was that the tomb of Bishop Maurus is shifted, with respect to the inscription placed in the middle of the crypt and supposed to indicate its position. Moreover, it was possible to detect the presence of another large cavity and estimate its size. During another training school held in 2016, the Jesuits' church in Valletta (Malta) was investigated [10].

The monuments and historical buildings assessed by using GPR in the framework of TU1208 also include: the Midas monument in the Eskisehir province of Turkey, dating back to the 7th or 6th century BC; the Sultan Alp Arslan Tomb of Merv in Turkestan, built in the 11th century; the

16th-century St. John's Cathedral and the botanical gardens in Valletta (Malta); the 17th-century Keciova Mosque of Casbah Algiers in Algeria; and more.

Historical bridges represent an important value from the architectural, historical, economical, symbolic and aesthetic points of view. They often characterize the landscape of a region and represent an integral part of its traditional architectonic heritage. Most bridges that remain from Roman and medieval times are stone-masonry arch bridges, which have lost their original utility and now have different functionality than those originally designated. Some of them are still part of the road infrastructure: their use causes a deterioration that demands constant evaluation and conservation activities, due to the strong loads and intense vibrations they have to support. When conservation stops, ruin and destruction soon set in. This has posed an important task for engineers and scientists, in terms of determining the state of conservation of historical bridges and to provide information about their preservation and restoration using non-destructive methods that do not change the historical character of the structure. Significant results were obtained by Action Members who used GPR to study ancient bridges in Spain. For example, hidden arches were discovered, the geometry of ancient profiles was deduced and evidence of restoration activities was found [11].

With the progress of the technology, lightweight GPR systems working above 2 GHz have been realized, providing a resolution of a few tenth of mm by means of specific processing. Consequently, new applications have become possible, such as the accurate assessment of the internal conditions of statues and architectural decorations. An interesting study carried out by TU1208 Members was concerned with testing five marble statues of the Antikythera Shipwreck collection, conserved in the National Archaeological Museum of Athens (Greece). All statues suffered substantial erosion because of their exposure to seawater for more than 2000 years. Most of them were found in parts and were reassembled by using metal joints, but conservation records were not kept. The dual purpose of the project was to detect, by using GPR, the presence of metallic joints in the statues as well as to identify hidden structural problems. The main challenge of the investigation was represented by the need to scan objects with undulated and rough surfaces. A GPR system with 2.4 GHz antenna was used. In most cases it was possible to successfully identify and locate the metal targets.

IV. ASSESSMENT OF NATURAL STRUCTURES OF HISTORICAL VALUE

Among the numerous studies carried out by TU1208 Members in the framework of the inspection of natural structures of historical value, let us provide the example

of the S-19 Cave in Slovenia [12]. This is one of the most important caves of the Mt. Kanin massif. After its discovery in 1974, a huge snow avalanche protection dyke was constructed across the cave entrance. GPR was used to determine the exact location of the entrance of the cave, in order to excavate it. Seven GPR profiles were measured in a local depression where the entrance was expected to be located, by using a ground-coupled 50 MHz antenna. Based on the GPR data interpretation, the most appropriate location for digging was determined and the thickness of debris assessed at about 7 m. A massive excavation by a dredger resulted in a successful opening of the cave entrance, confirming both its estimated location and depth. The application of an advanced geophysical method was therefore proven successful in providing a solution to this specific case study and an important cave was saved.

V. CONCLUSIONS

This paper, submitted by the organizers of the 2017 MetroArchaeo Special Session "Ground Penetrating Radar for archaeological prospection and cultural-heritage management," aims at disseminating the research activities carried out by the Members of the COST Action TU1208 "Civil Engineering Applications of Ground-Penetrating Radar" in the areas covered by the Session.

Large-scale inspections, as well as investigations performed at archaeological sites of more limited extent, were briefly mentioned. A short review of further studies was given, where structures of great historical value and from different time periods were prospected, ranging from the 13th century BC to the modernist period and including tombs, monuments, cathedrals, buildings, bridges and statues. An example of application of the GPR technique to the inspection of a natural structure of historical value was given. TU1208 educational activities were mentioned.

VI. ACKNOWLEDGEMENTS

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