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IAG/USP TEST SITE: A NEAR SURFACE GEOPHYSICS TEACHING AND RESEARCH LABORATORY

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ABSTRACT. This work shows the construction project of the Geophysical Test Site (Sítio Controlado de Geofísica Rasa, SCGR-I) of the Institute of Astronomy, Geophysics and Atmospheric Sciences (IAG), of the University of São Paulo (USP) and its impact on teaching and research in Geophysics. The IAG/USP test site (SCGR-I) has 1500 m^2, being characterized by 7 studies lines with 30 m length in the NS direction. Targets, such as metallic pipes and tanks, plastic pipes and tanks, concrete tubes, ceramic pots, among others, with different geometries and physical properties were buried at depths from 0.5 to 2 m in relation to the surface. A metallic guide pipe of 3.8 cm of diameter was buried at the 15 m position along the EW direction, crossing all 7 lines. Targets simulate objects found in archaeological studies, geotechnical and urban planning studies and environmental studies. In this work, comparative analyzes between real and synthetic GPR results on metallic and plastic tanks are shown, as well as EM38 results on metallic tanks. The SCGR-I proved to be an important tool for teaching and research related to the applications of geophysical methods for near surface investigations and could be a motivation to build more test sites.

Keywords: IAG/USP Test Site; non-destructive testing; GPR; EM38; USP.

INTRODUCTION

Since 1993, São Paulo campus of the University of São Paulo (USP) has been used as a applied geophysics laboratory, but only in 1997 the area in front of the Institute of Astronomy, Geophysics and Atmospheric Sciences (IAG/USP) began to be systematically used as a laboratory for practical activities by undergraduate and graduate students in geophysics.

In these systematic surveys, several geophysical methods were used, such as GPR-Ground Penetrating Radar, resistivity, capacitive resistivity, inductive electromagnetic, refraction seismic and magnetometry. The results showed how near surface investigation problems applied to engineering, urban planning, environment and archaeology can become complex in terms of data interpretation. Despite the good results, the ambiguity in the interpretation process about the geological features persisted. These questions served as a source of motivation for the construction of an area for controlled tests of near surface geophysics, where several geophysical methods could be used and their results compared against lithological data from wells and the physical and geometric properties of known targets.

In this sense, with the support of FAPESP-Fundação de Amparo à Pesquisa no Estado de São Paulo in December 2003, the first Geophysical Test Site or Sítio Controlado de Geofísica Rasa (SCGR-I) of the IAG/USP, pioneer in Brazil, was built. SCGR-I is located on the edge of the São Paulo sedimentary basin, within the USP campus. The buried targets, such as metallic pipes and tanks, plastic pipes and tanks, concrete tubes, ceramic pots, among others, simulate some real situations in engineering works, urban planning, environmental contamination studies and in archaeological research. The importance of this test site is that the geophysical signatures of targets whose physical and geometric properties are known can be used as standard responses for each type of material and can be extrapolated to areas where subsurface information is not available.

SCGR-I constitutes an important tool for teaching and research in geophysics, and will be of great importance to our community, consisting of a new underground laboratory. With the installation of the SCGR-I, an important step was taken to improve the knowledge regarding the geophysical responses of targets found in environmental, engineering and archaeology studies.

To illustrate it, numerical modeling results are presented by the FDTD - Finite Differences in Time Domain method, which simulates the responses from the GPR reflections on the metallic tanks installed on Line 4 and the plastic tanks installed on Line 5 of SCGR-I, as well as the GPR results on the same targets. Additionally, the results obtained with the inductive electromagnetic method using the EM38 equipment on the metallic tanks are also presented.

The present work summarizes the construction project of the IAG/USP Test Site (SCGR-I), shows the comparative results of numerical modeling GPR 2D and real data, EM38 results over metallic tanks and ends with the impacts on teaching and research activities in near surface geophysics.

LOCAL GEOLOGICAL ASPECTS

SCGR-I of the IAG/USP is installed on the edge of the São Paulo sedimentary basin, within the campus of the University of São Paulo in São Paulo city, and is inserted in a geological-urban context different from other existing test sites abroad. The location of the São Paulo city is largely based on this basin, and the implementation of important works, such as the construction of the Metro and the Guarulhos international airport, greatly favored the knowledge of its geology.

The geological knowledge of the São Paulo basin was obtained mainly through direct information from excavations, surveys and through geological mapping carried out in the 1970's and 1980's. Due to technological development and the increasing urbanization of the city of São Paulo, the exposed soil of the basin was paved and waterproofed, making it difficult to study the basin through geological surveys and direct investigations. Therefore, the geophysical methods of indirect investigation have become indispensable tools for the geological and geotechnical knowledge of the São Paulo basin.

Geological information for the São Paulo basin in the SCGR-I area was obtained through the lithology of three wells for geological and geophysical research that were drilled in the study area (Porsani et al., 2004). Figure 1 shows the location of the study area with the position of the three wells drilled.

Geologically, the SCGR-I area consists of an embankment, characterized by sandy to silty clay, with some levels of silt, sometimes clayey, sometimes sandy, predominantly dark red, with a thickness of less than 3 m. A neocenozoic cover is observed up to 6 m depth, being evidenced by clays enriched in organic matter. From there, 53 meters thick of sand-clay sediments from the Resende and São Paulo Formations predominate, superimposed on the granite-gneissic basement (Borges, 2007).

SCGR-I of the IAG/USP: Constructive Project

The constructive project of the SCGR-I is presented, aiming to serve as an inspiration for the construction of other Test Sites in near surface geophysics. SCGR-I of the IAG/USP has an area of 1500 m^2 , and it is located in front of the Institute of Astronomy, Geophysics and Atmospheric Sciences (Figure 1).

It is composed of 7 studies lines of 30 m each, arranged along the magnetic N-S direction. A guide metal pipe with a diameter of 3.8 cm was installed at the 15 m position along 50 m in the E-W direction, serving as a target-guide that crosses all 7 lines of study.

The targets were grouped by specific types of materials and placed at depths whose top varies from 0.5 to 2 m in relation to the surface. The targets were installed with magnetic N-S direction or EW orientations, followed by a topographic survey with a total station to accurately determine the positioning and depth of the top of the targets in relation to the terrain surface.

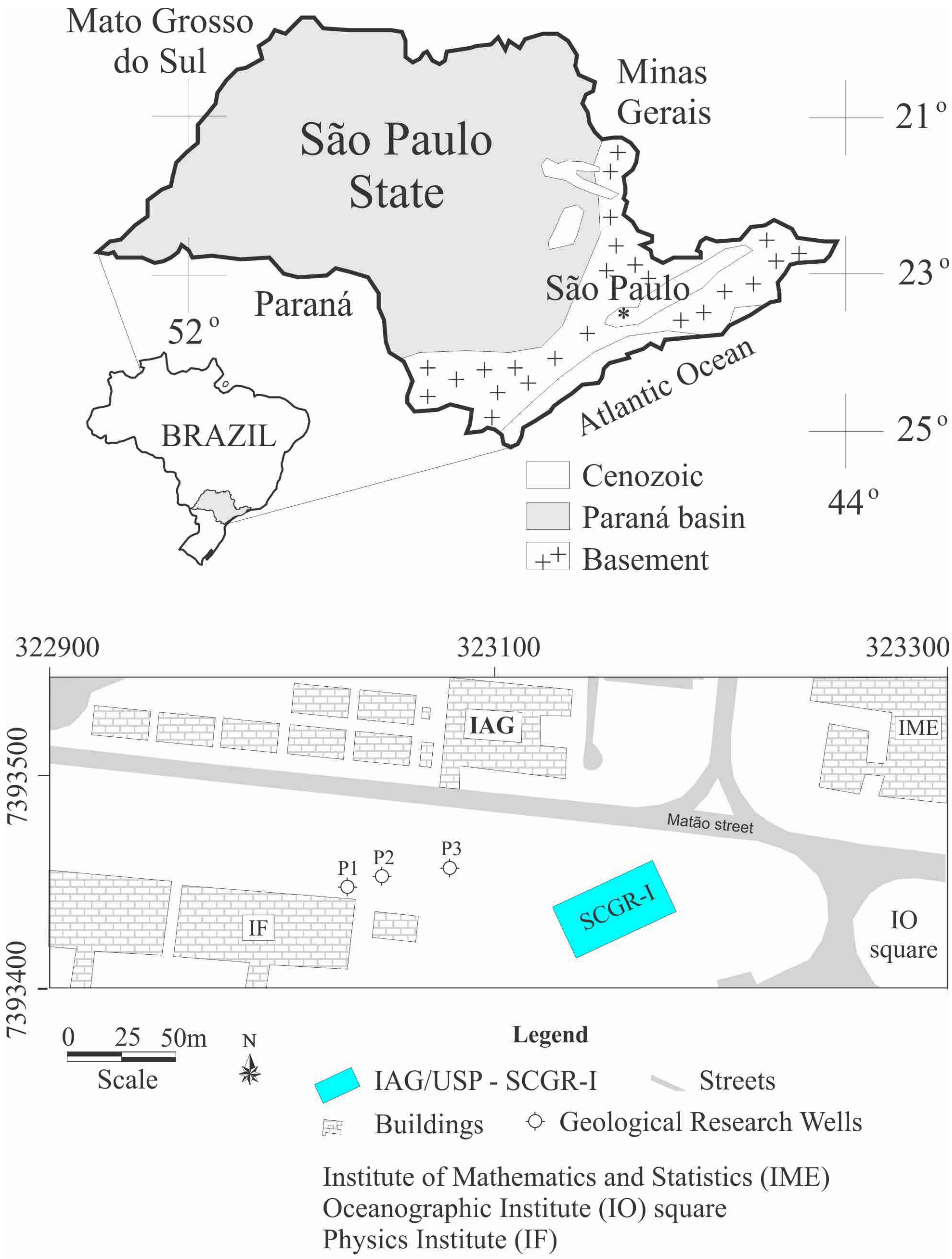

Figure 1: Location map of SCGR-I geophysical test site of IAG/USP, in São Paulo city.

The targets were chosen to have magnetic or conductive responses or to generate reflections in the GPR profiles. Figure 2 shows the base map of the SCGR-I of the IAG/USP with the control marks, location of the 7 studies lines, the guide metal pipe and the position of the trees on the surface of the land.

Figure 3 shows the targets buried in Line 1 that aimed to contemplate archaeological studies. In this line were buried sandboxes and granite gravel, turned soil, brick wall, ceramic pots and a small layer of quartz pebbles. The ceramic pots were buried empty and simulate underground tunnels, the brick wall simulates the foundation of historic churches and the pebble layer simulates a paleofire.

Line 2 (Figure 4) is constituted by brown High Density Polyethylene (PAD - Polietileno de Alta Densidade) pipes with a diameter of 11 cm and 2 m in length. PAD pipes simulate the transport of drinking water to homes, and they are often found in large cities. These pipes are used by the Basic Sanitation Company of the State of São Paulo (SABESP).

Figure 5 shows the targets buried in Line 3 which is characterized by concrete tubes of 26, 48 and 70 cm in diameter. The tubes simulate rainwater channeling galleries and sewage drainage.

Line 4 (Figure 6) is characterized by 200 liter metallic tanks that were arranged both horizontally and vertically, individually and in pairs. All tanks were buried empty to avoid corrosion problems. This line

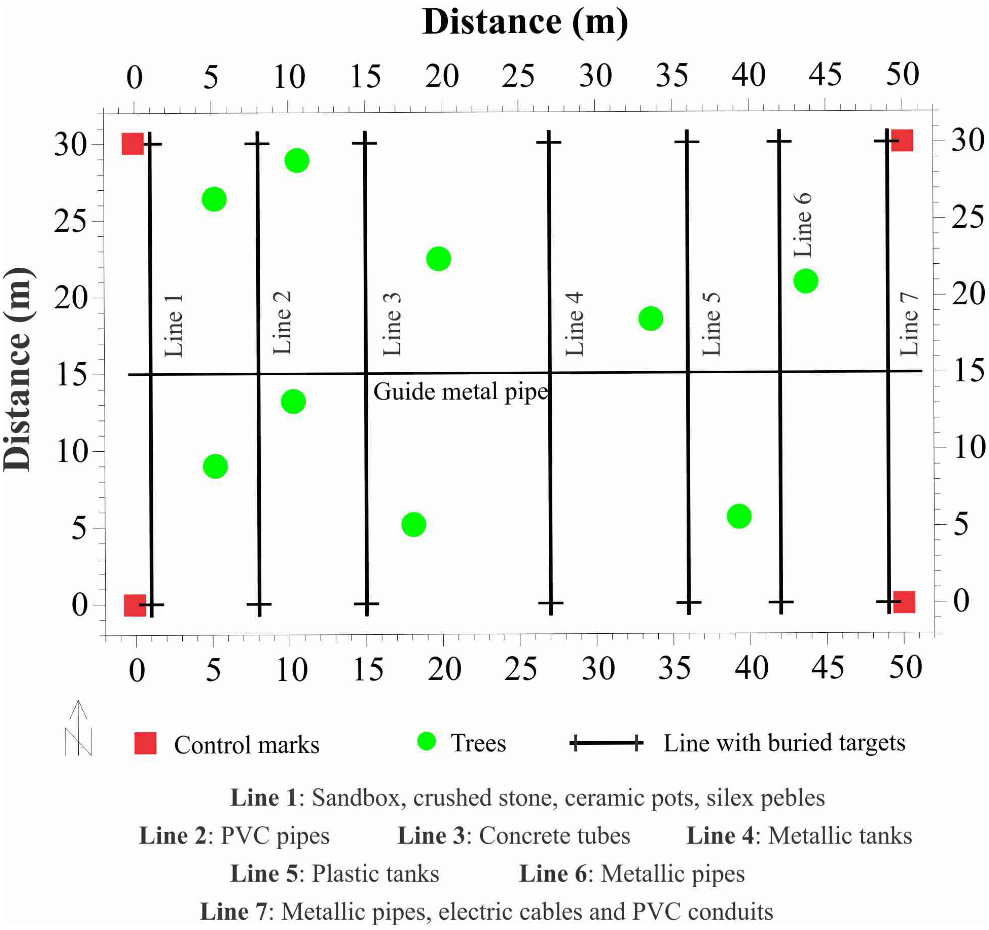

Figure 2: Base map of the SCGR-I of the IAG/USP with the control marks, location of the 7 studies lines, the guide metal pipe and the position of the trees on the surface of the land.

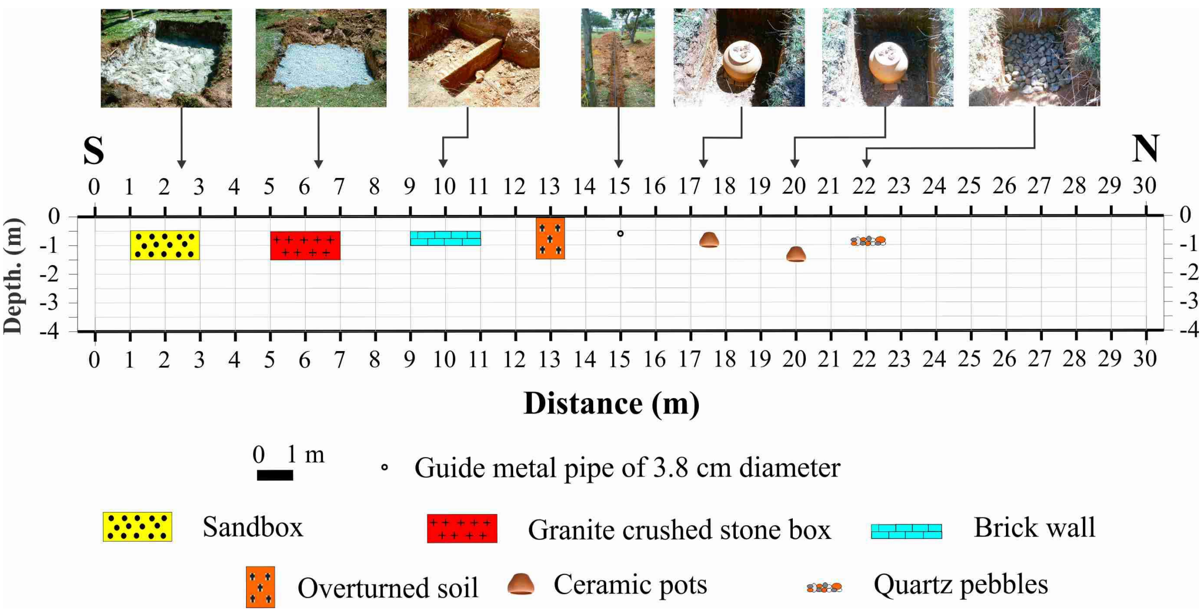

Figure 3: A sketch of the Line 1 of SCGR-I, showing the buried targets and their positions, simulating archaeological studies.

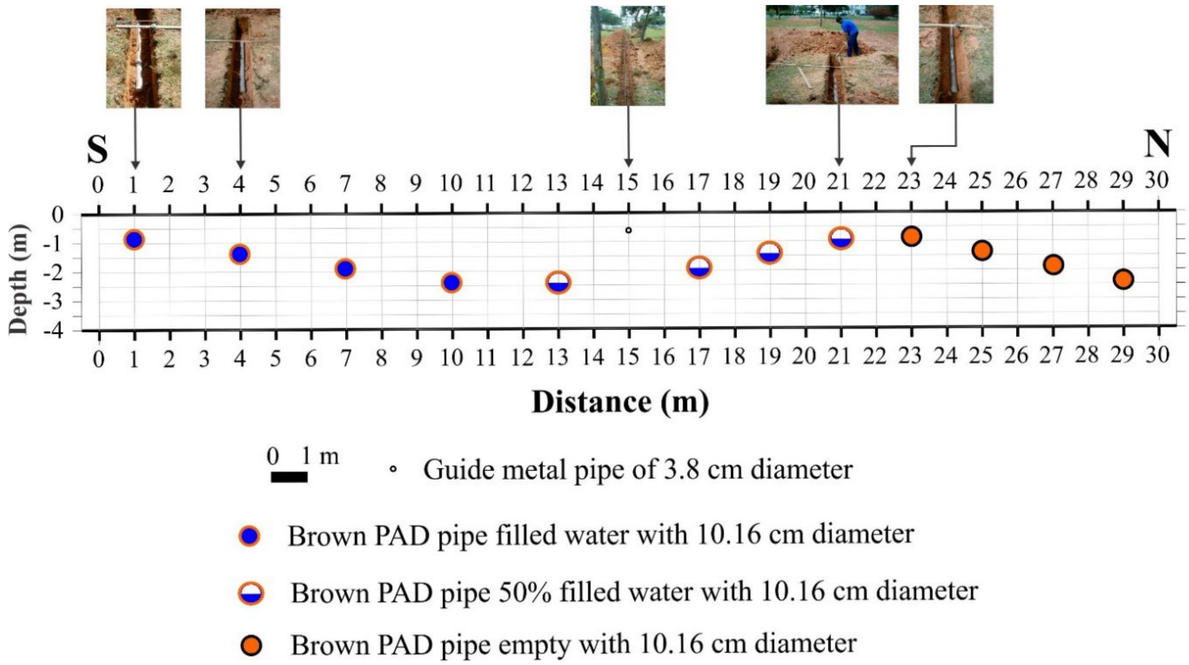

Figure 4: A sketch of the Line 2 of SCGR-I, showing brown High Density Polyethylene (PAD - Polietileno de Alta Densidade) pipes with a diameter of 11 cm, that simulate urban planning studies aiming at subsurface interference mapping.

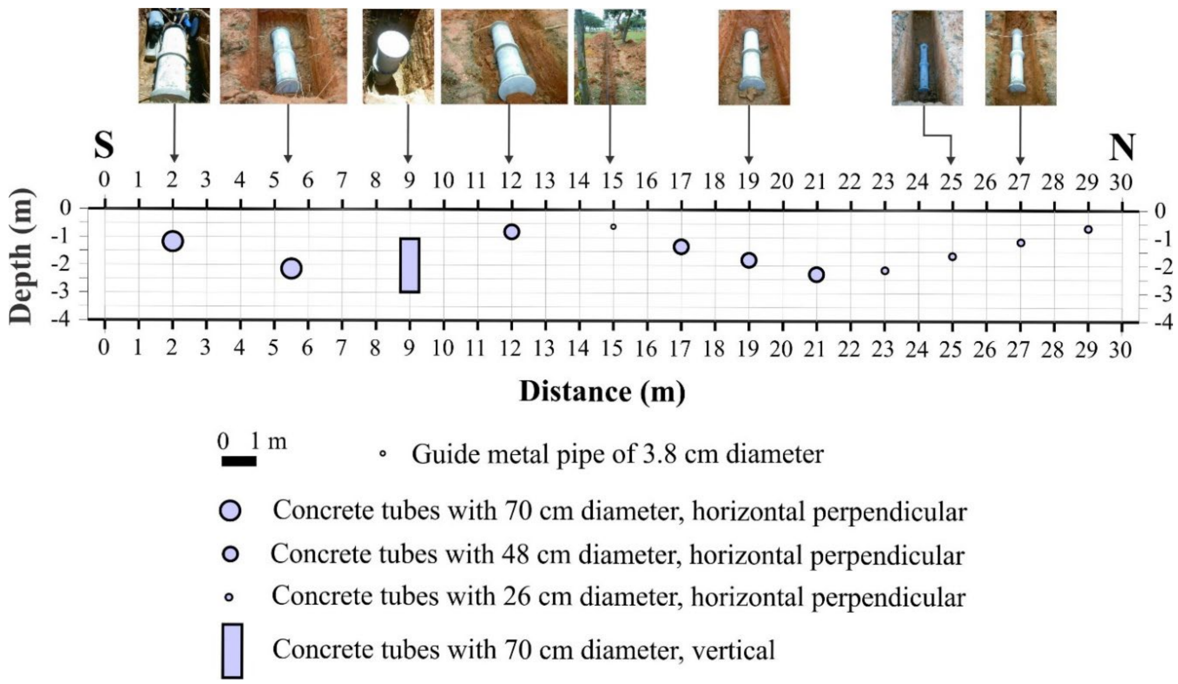

Figure 5: A sketch of the Line 3 of SCGR-I, showing concrete tubes of 26, 48 and 70 cm in diameter, that simulate urban planning studies aiming at subsurface interference mapping.

aims to simulate environmental studies, whose goal is the location and determination of their depths.

Figure 7 shows the targets installed on Line 5 which are characterized by 100 liters plastic tanks. Plastic tanks also simulate environmental studies, for example, the resistive contaminant is represented by an empty tank and a tank filled with water; and the conductive contaminant is represented by tank filled with brine and tank partially filled with brine. The electrical conductivity of brine was measured in a chemical analysis laboratory at the Oceanographic Institute at USP and corresponds to 980 mS/m.

In Line 6 (Figure 8) metallic pipes measuring 10.5 cm in diameter and 2 m in length were installed. The pipes are used for the passage of gas by the São Paulo Gas Company (COMGAS) and for the transport of potable water used by SABESP.

Figure 9 shows the targets installed on Line 7, characterized by metallic pipes with a diameter of 21 cm and 2 m in length, plastic conduits for the passage of optic fiber cables, non-energized electrical cables arranged underground and enveloped electrical ducts in concrete boxes. Metallic pipes simulate the passage of gas and potable water to homes. The plastic conduits serve to simulate the passage of optic fiber cables used by telecommunications companies. Non-energized electrical cables and electrical ducts enveloped in concrete are frequently used by ENEL - Distribuição São Paulo, old Cia ELETROPAULO.

Figures 2 to 9 show the "mine map" with the precise location of the targets installed in the SCGR-I, which allows for a comparison with the real geophysical data acquired at each line. This information is important to calibrate the geophysical responses, and thus reduce the ambiguity in the interpretation of the real data.

All materials installed in the SCGR-I aim to simulate a small sample of the main targets that are normally found underground in large urban centers and in some archaeological sites. With the installation of the test site of the IAG/USP, different geophysical methods of near surface investigation were evaluated for performance and reliability when applied to urban problems, aiming at mapping subsurface interference, studies of environmental contamination and in archaeological research. The results of many of these works are published in the literature, such as: Porsani et al. (2004, 2006, 2010, 2017, 2018); Rodrigues and Porsani (2006); Porsani and Sauck (2007); Santos and Porsani (2011); Santos et al. (2014, 2018); Poluha et al. (2017); among others.

GPR 2D Numerical Processing and Modeling

Data processing was performed using the Radan 7 software (GSSI). The main steps used were: zero time correction, spatial and temporal bandpass filtering, time-varying gains and time/depth conversion. For a time to depth conversion, a velocity of 0.065m/ns was used, which corresponds to the sandy clay soils of the SCGR-I area. This speed was calculated based on the time measurement (read in radargram) and the depth of one of the metallic tanks. With the double time-t and the depth-h, so substitute them in the expression of the transit time v=2h/t to obtain the propagation speed of the electromagnetic wave of the GPR in the medium.

To give more reliability to the interpretation and analysis of the GPR profiles above the metallic and plastic tanks installed in the SCGR-I, complementary 2D GPR numerical modeling studies were carried out using the ReflexW software (Sandmeier, 2020). The simulation of electromagnetic wave propagation in a 2D model was based on the solution of Maxwell's equations through the finite difference method in the time domain-FDTD (Ward and Hohmann, 1987).

Numerical modeling is of great importance to predict the results to be obtained in a real field situation or serve to prove the real results through a comparative study. For simulations of the GPR profiles, antennas with a central frequency of 150 MHz and polarization of the electric field-Ey were used, which corresponds to the configuration of the antennas perpendicular to the direction of the profile (Radzevicius and Daniels, 2000; Porsani et al., 2010). The wave field was simulated using an "exploding reflector" source, in which waves are generated simultaneously from the target and sent to the surface (Yilmaz, 1987; Daniels, 1996). This procedure corresponds to the repositioning of the diffraction hyperbolas in the targets, collapsing the energy to the apex of the hyperbola, being a common procedure in the step of GPR and seismic data migration.

RESULTS DISCUSSION

GPR Profiles

Figure 10 shows the comparison between the results of the 2D GPR numerical modeling and the 200 MHz GPR profile on line 4 of the SCGR-I consisting of metallic tanks. Figure 10a shows the results of the GPR numerical modeling for 150 MHz. Note that only the top of the targets is determined by the simulation, being characterized by strong hyperbolic reflections due to the high electrical conductivity of the metal (10^9 mS/m). In this case, all the energy of the electromagnetic wave of the GPR is reflected in the metal. Note that the reflection pattern on the vertical tanks is different from the horizontal tanks, that is, the shape of the target influences the reflection pattern.

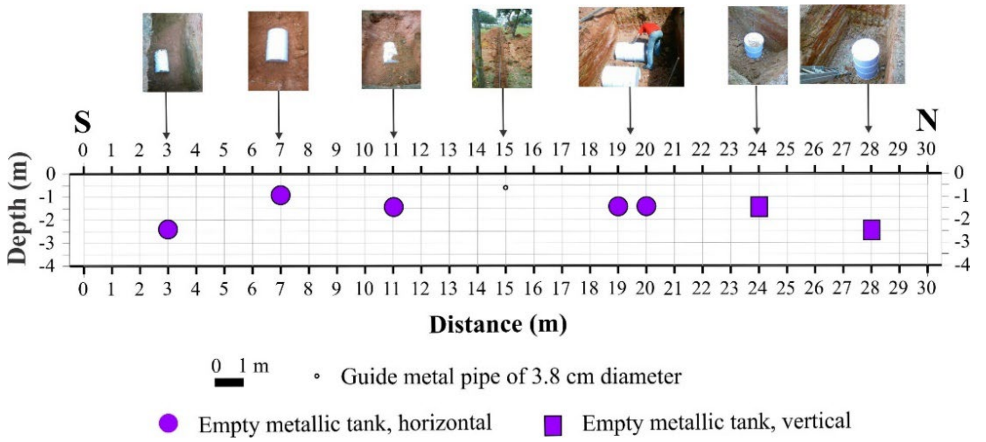

Figure 6: A sketch of the Line 4 of SCGR-I, showing 200 liters metallic tanks that were arranged both horizontally and vertically positions, individually and in pairs, simulating environmental studies.

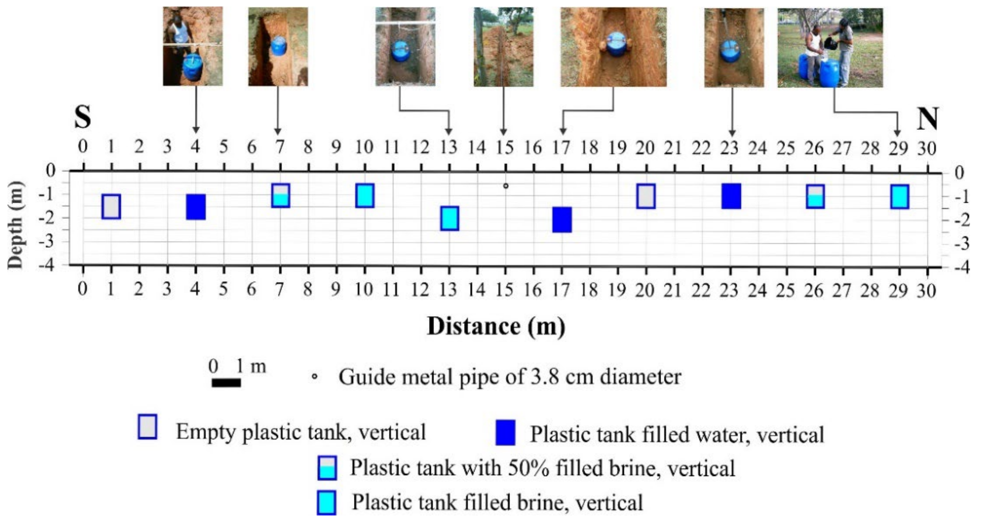

Figure 7: A sketch of the Line 5 of SCGR-I, showing 100 liters plastic tanks arranged in vertically position, simulating environmental studies.

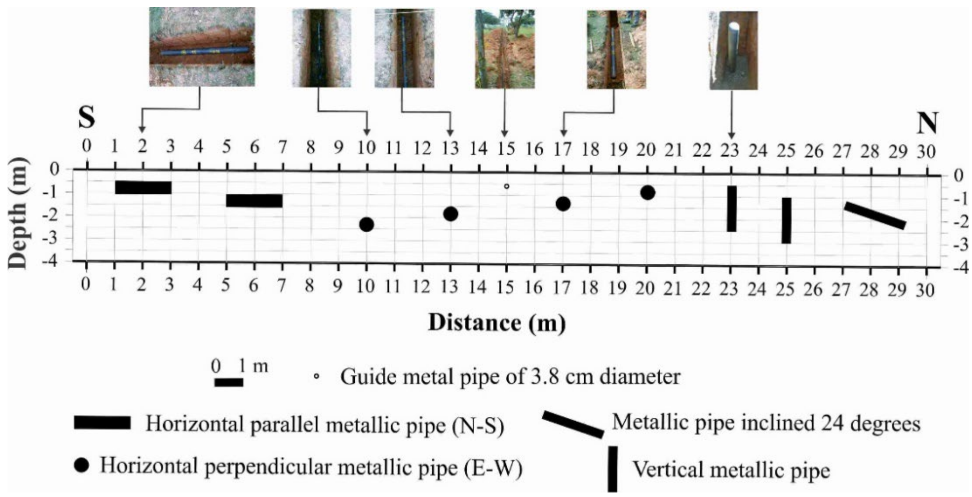

Figure 8: A sketch of the Line 6 of SCGR-I, showing metallic pipes with a diameter of 10.5 cm arranged in the horizontally, vertically and inclined positions, that simulate urban planning studies aiming at subsurface interference mapping.

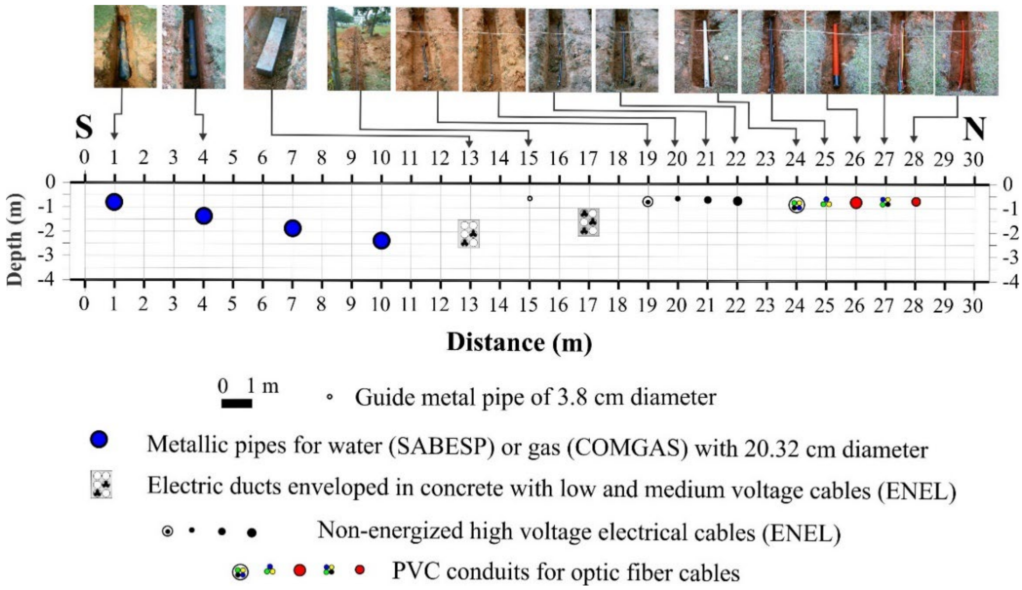

Figure 9: A sketch of the Line 7 of SCGR-I, showing metallic pipes with a diameter of 21 cm, plastic conduits for the passage of optic fiber cables, non-energized electrical cables and concrete box enveloped electrical ducts, that simulate urban planning studies aiming at subsurface interference mapping.

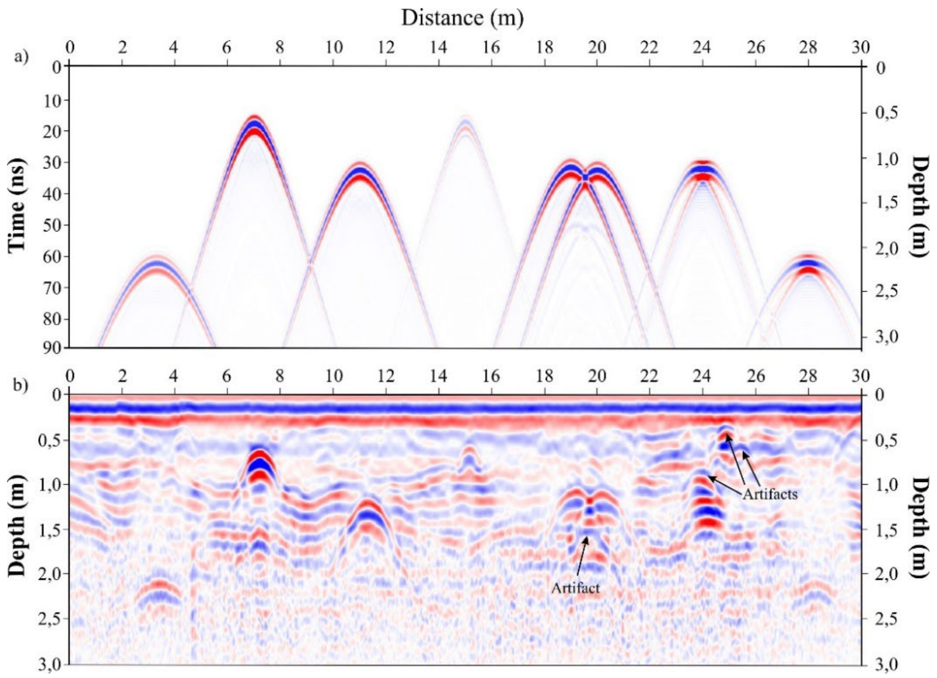

Figure 10: GPR numerical modeling and GPR profiles over all the metallic tanks buried in Line 4 of the IAG/USP test site (SCGR-I). a) Numerical modeling of 150 MHz GPR profile. b) 200 MHz GPR profile.

Figure 10b shows the 200 MHz GPR profile results. It is observed that the top of the metallic tanks is characterized by strong hyperbolic reflections, which was expected, as shown in the numerical modeling result (Figure 10a). Note a hyperbolic reflection at position 19.5 m and arranged at a depth of 1.5 m, highlighted in Figure 10b by an arrow. This reflection, called "artifact", corresponds to a constructive interference of the reflection of the GPR signal between the tank at the 19 m position and the tank at the 20 m position. A detailed discussion of the identification and removal of this artifact through effective processing of the GPR data can be found in

Porsani and Sauck (2007). Also note three other hyperbolic reflections (“artifacts”) under positions 24, 25 and 25.5 m, being related to voids in the subsoil due to poor soil compaction. These three anomalies were confirmed by means of auger boreholes.

The guide metal pipe arranged at 15 m position and at 0.5 m depth is characterized by a tighter hyperbolic reflection. Note that from 2.5 m depth, the GPR signal is attenuated due to the conductive characteristics of the sediments of the São Paulo basin (Porsani et al., 2004).

Figure 11 shows the comparison between the results of the 2D GPR numerical modeling and the 200 MHz GPR profile on line 5 of the SCGR-I consisting of plastic tanks. Figure 11a shows the results of the GPR numerical modeling for 150 MHz. It is observed that the plastic tanks and the guide metal pipe are characterized by hyperbolic reflections generated at the top of the targets, whose apex indicates their underground positions. It is noted that the tanks filled with water are characterized by reflections generated at the top and bottom. Additionally, it is also observed that the tanks filled with water and brine present reflections with inverted polarity compared to the top of the empty tanks.

Figure 11b shows the 200 MHz GPR profile results. The empty plastic tanks arranged at positions 1 and 20 m are characterized by strong hyperbolic reflections at the top. The bottom of the tanks is not detected due to overlapping reflections at the top and bottom of the tank. For the tanks filled with water arranged at positions 4, 17 and 23 m, two reflections are observed at different times. The first reflector characterizes the top and the second reflector is related to the base of the tank. Note also that the reflectors at the top of the tanks present an inversion of polarity in relation to the reflections generated at the top of the empty tanks due to the high impedance contrast between the clayey soil and the water. A more detailed discussion on identifying the polarity change of the GPR signal can be found in Rodrigues and Porsani (2006).

The half-filled tanks with brine arranged at positions 7 and 26 m were characterized by reflections generated at the soil/plastic/air interface. The upper limit of the brine is not detected, due to the overlap of the reflections at the top of the tank (empty part) and the top of the brine, similar to the empty tanks. The base of these tanks is also not determined due to the high electrical conductivity of brine, causing a high attenuation of the GPR signal.

Tanks filled with brine arranged at positions 10, 13 and 29 m are characterized by reflections with reversed signal polarity generated at the top of the targets, similar to tanks filled with water. Note that the base of the tanks is not detected, due to the attenuation of the electromagnetic wave in brine which is very conductive.

The guide metal pipe arranged at a 15 m position and at a depth of 0.5 m, served as a reference target for all seven lines of studies installed at SCGR-I. The top of the metallic pipe is characterized by a strong reflection due to the high electrical conductivity of the metal, causing a total reflection of the GPR signal.

EM38 Profile

Geophysical methods have been important in detecting underground objects such as communication cables, pipes and other public infrastructure. Electromagnetic systems operating in the frequency domain have been shown to be suitable and efficient in detecting buried metallic objects, with several examples in studies of unexploded ordnance detection, urban interference and archaeology (Nelson et al., 2007; Qu et al., 2017).

GPR has been successfully used to detect buried objects and interference networks underground. However, it has limitations to detect objects buried in conductive saturated clayey soils. On the other hand, the electromagnetic frequency domain system (EM38) does not suffer this limitation in the case of metallic objects buried in conductive environments. Therefore, the integrated application of GPR and EM38 can be complementary, improving the ability to detect metallic targets arranged in conductive soils.

In this work, Geonics EM38 equipment was used to detect metallic tanks buried in SCGR-I. A profile of 30 meters in length was acquired with measurements spaced of 1 meter. The equipment allows a maximum theoretical investigation depth of 1.5 meters, being indicated only for mapping shallow targets. The measurements were performed with the coils in the vertical and horizontal positions, so that two theoretical depths were obtained at each station. Data collected at two investigation depths were entered into inversion program which provided a 2D section of the conductivity profile.

For the interpretation of the EM38 profile on the metallic tanks, the inversion program called EM34-2D was used (Monteiro Santos, 2004). This program uses the non-linear inversion algorithm presented in Sasaki (1989). The algorithm uses a smoothness constraint regularized inversion technique for electromagnetic data acquired along profiles. The algorithm corresponds to a modified 1D inversion with 2D smoothness constraints between adjacent 1D models. Thus, it is possible to obtain the answer in terms of the variation of electrical conductivity and real depths for the measurement points that, interpolated, allow the creation of a 2D image.

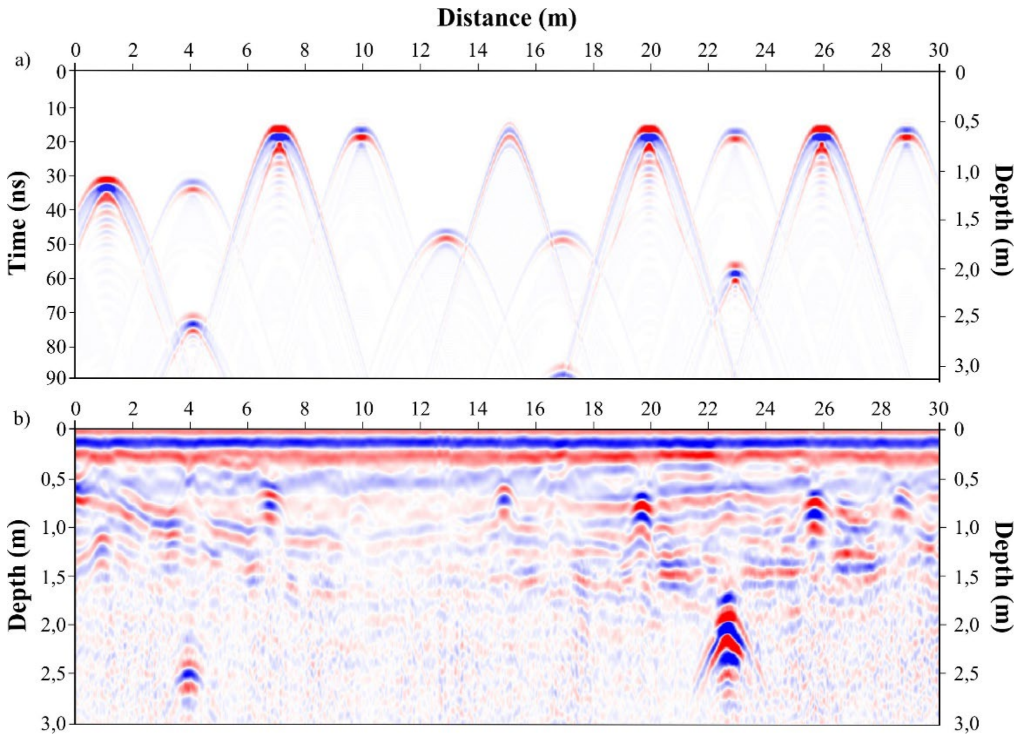

Figure 11: GPR numerical modeling and GPR profiles over all the plastic tanks buried in Line 5 of the IAG/USP test site (SCGR-I). a) Numerical modeling of 150 MHz GPR profile. b) 200 MHz GPR profile.

Figure 12 shows the result of the 2D inversion of the inductive electromagnetic profile, acquired with the EM38 equipment, on line 4 of the SCGR-I with the location of the metallic tanks. It is possible to observe that the metallic tanks installed horizontally and vertically at the depths where the equipment has reach were clearly detected by anomalies of high electrical conductivity values. Tanks that are installed up to 1.5 m deep were detected with good accuracy. This shows that EM38 can be very efficient in detecting buried metallic objects up to 1 meter deep, and its application integrated with GPR is interesting, especially in conductive soils. Note that the guide metal pipe installed at 0.5 m depth was not clearly detected. This fact is due to its small dimensions, i.e., 3.8 cm in diameter, which is below the detection limit of the EM38 equipment.

IMPACTS ON TEACHING AND RESEARCH IN NEAR SURFACE GEOPHYSICS

SCGR-I of the IAG/USP allows testing different methodologies for interference mapping, as well as equipment calibration and testing of new numerical simulation algorithms. This underground laboratory is being used by undergraduate and graduate students, where students become familiar with the "modus operandis" of geophysical equipment.

The practical activities of mapping underground targets, whose physical and geometric properties are known, are important because the geophysical signatures of real targets, such as metal and plastic pipes, metal and plastic tanks, and concrete tubes, among others, usually found in large cities can be extrapolated to places where subsurface information is not available. The results benefit the research lines in near surface geophysics of the Department of Geophysics and have direct applications in the mapping of interferences in the subsoil, being important for an integrated management of smart cities.

The results of these researches applied in partnership with the students were published in the form of scientific articles in journals and in the annals of international conferences, as well as in the form of software records with the USP Innovation Agency. Among the studies published in the literature are: Porsani et al. (2004, 2006, 2010, 2017, 2018); Rodrigues (2004); Lima (2006); Rodrigues and Porsani (2006); Porsani and Sauck (2007); Borges (2007); Santos (2009); Santos and Porsani (2011); Santos (2014); Santos et al. (2014, 2018); Almeida (2016), Poluha (2017); Poluha et al. (2017), among others.

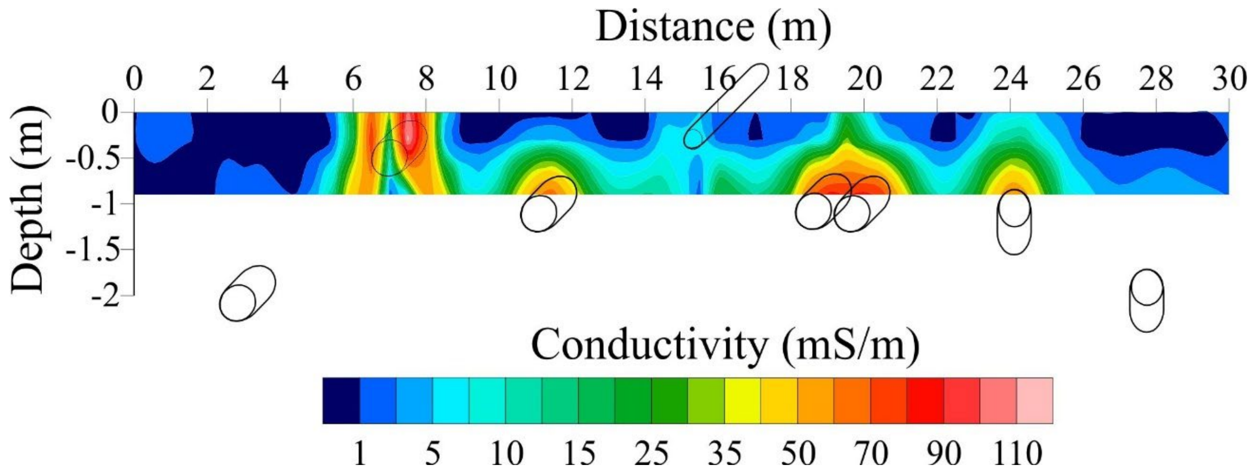

Figure 12: 2D inversion of the EM38 profile over all the metallic tanks buried in Line 4 of the IAG/USP test site (SCGR-I) with the location of the metallic tanks overlapping.

The development of research at SCGR-I is allowing to increase the visibility of research carried out by the Applied Geophysics Group of the Department of Geophysics at IAG/USP on the national scene, for instance, PETROBRAS, COMGAS, METRÔ, ANEEL, among other companies.

The main beneficiaries of the research developed at the SCGR-I of the IAG/USP are the undergraduate and graduate students in Geophysics, in addition to the society that benefits from the knowledge developed at the University through the University Extension courses, such as: "Schools of Geophysics Summer", the events "USP and Professions" and "Science and Technology Week". In this way, the impact of the construction of the SCGR-I is being positively reflected in teaching and research, and will be of great value to new students for the next 10 or 20 years.

Final Remarks

The SCGR-I built in 2003, and since its construction it has been used for calibration and testing of equipment and new software for modeling and inversion of geophysical data, constituting an important tool for teaching and research in near surface geophysics. In order to expand the types of targets underground, in 2015, with the support of COMGAS, the SCGR-II of the IAG/USP was built, constituting a complete teaching and research laboratory for mapping utility distribution networks in the underground, increasing the visibility of the Applied Geophysics Group of the Geophysics Department at IAG/USP.

CONCLUSIONS

With the construction of the SCGR-I of the IAG/USP we gave an important step towards the "State of the Art in Near Surface Geophysics in Brazil", which allowed the development of new software for modeling and inversion of geophysical data and its responses were calibrated against targets whose geometries and physical properties were known.

The geophysical characterization of metallic and plastic tanks, under controlled field conditions in SCGR-I, allowed a calibration of the geophysical responses. Geophysical signatures can be used as typical standard responses and extrapolated to areas where subsurface information is not available. This type of characterization is important for testing and calibrating the various geophysical methods that are routinely used in geological, geotechnical, environmental and archaeological studies.

2D GPR numerical modeling studies by the FDTD method proved to be important to predict the real results and prove the typical patterns of reflections on metallic and plastic tanks buried in the SCGR-I of the IAG/USP.

Finally, we hope that the presentation of the constructive project of the Geophysical Test Site (SCGR-I) of the IAG/USP could serve as a reference guide for the construction of new geophysical test sites.

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