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Feasibility Study of Buried Explosive Detection using GPR (Ground Penetrating Radar)
Andreia Machado Brito da Costa

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ANDREIA MACHADO BRITO DA COSTA

Dissertation for the Degree of Master in Forensic Sciences and Laboratory Techniques

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Submitted to the University Institute of Health Sciences

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DECLARAÇÃO DE INTEGRIDADE

Eu, **Andreia Machado Brito da Costa**, estudante do **Mestrado em Ciências e Técnicas Laboratoriais Forenses** do Instituto Universitário de Ciências da Saúde, declaro ter atuado com absoluta integridade na elaboração desta Dissertação.

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Gandra, outubro 2019

A Estudante,

Andreia Machado Brito da Costa

To my mom and sister

SCIENTIFIC PRODUCTION

Scientific articles in international journals:

Costa, A., Rodrigues, D., Borges, J., Almeida, F., Fernandes, L., Moura, R., Madureira-Carvalho, Á. 2019. Testing a 2D Ground-penetrating radar towards the detection of explosive targets buried in Portuguese soils (submitted to IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS); Attachment 1).

Costa, A., Martins, D., Rodrigues, D., Fernandes, L., Moura, R., Madureira-Carvalho, Á. 2019. Ground Penetrating Radar for Buried explosive Devices Detection: A Case Studies Review (submitted to Forensic Science International; Attachment 2).

Costa, A., Madureira-Carvalho, Á, Moura, R., Rodrigues, D., Fernandes, L., Gomes, C., Silva, R., Borges, J., Almeida, F. 2019. Use of a 3D Ground-Penetrating radar (GPR) for detection of buried inert explosive devices, SGEM Conference Proceedings 2019, Section Applied and Environmental Geophysics, p. 983-990 (Attachment 3).

Communications in International Congresses:

Panel presentation

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Communications in National Congresses:

Panel presentation

Costa, A., Gomes, C., Silva, R., Rodrigues, D., Borges, J., Almeida, F., Fernandes, L., Moura, R., Madureira-Carvalho, Á. 2019. Geophysical detection of explosive dev ices buried in different types of Portuguese soils. IV Congresso da Associação Portuguesa de Ciências Forenses/ XIII Jornadas Científicas de Ciências do Instituto Universitário de Ciências da Saúde, Livro de resumos, Comunicação em poster nº 119, p. 201-202 (Attachment 5).

Gomes, C., **Costa, A.**, Silva, R., Rodrigues, D., Borges, J., Almeida, F., Fernandes, L., Moura, R., Madureira-Carvalho, Á. 2019. A utilização de dois georadares (2D e 3D) para deteção e identificação de engenhos explosivos enterrados: estudo comparativo. IV Congresso da Associação Portuguesa de Ciências Forenses/ XIII Jornadas Científicas de Ciências do Instituto Universitário de Ciências da Saúde, Livro de resumos, Comunicação em poster nº 115, p. 195-196 (Attachment 6).

Costa, A., Martins, D., Rodrigues, D., Borges, J., Almeida, F., Fernandes, L., Moura, R., Madureira-Carvalho, Á. 2018. The use of ground penetrating radar for detection of buried explosive devices. III Congresso da Associação Portuguesa de Ciências Forenses/ XII Jornadas Científicas de Ciências do Instituto Universitário de Ciências da Saúde, Livro de resumos, Comunicação em poster nº 68, p. 107-109 (Attachment 7).

Martins, D., **Costa, A.**, Rodrigues, D., Borges, J., Almeida, F., Fernandes, L., Moura, R., Madureira-Carvalho, Á. 2018. Deteção geofísica de engenhos explosivos. III Congresso da Associação Portuguesa de Ciências Forenses/ XII Jornadas Científicas de Ciências do Instituto Universitário de Ciências da Saúde, Livro de resumos, Comunicação em poster nº 77, p. 119-121 (Attachment 8).

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RESUMO

É comum, em investigações forenses, a existência da necessidade de detetar materiais enterrados (*e.g.* cadáveres, armas, engenhos explosivos), possivelmente relacionados com crimes ocorridos. A sua procura e deteção deve ser realizada da forma menos dispendiosa e mais rápida possível, através de metodologias não-destrutivas. Os métodos geofísicos cumprem com tais requisitos, sendo o georadar (*Ground Penetrating Radar* - *GPR*) já regularmente utilizado, inclusivamente na deteção de engenhos explosivos enterrados.

Com o presente trabalho pretendeu-se avaliar o desempenho de dois sistemas de georadares, na deteção e identificação de diferentes engenhos explosivos, enterrados no seu estado inerte, tendo em consideração algumas variáveis contextuais (frequência da antena de GPR; condições ambientais; tipo de solo; tipo de material de revestimento dos engenhos explosivos e profundidade de enterramento dos mesmos). Para tal, realizaram-se varrimentos com o sistema de GPR 2D-Easyrad, utilizando-se duas antenas (300 MHz e 100 MHz), durante um ano (quatro estações), estando os materiais enterrados em duas tipologias de solo (arenoso e argiloso). No inverno, foi também utilizado o sistema de GPR 3D-Radar. Em cada tipologia de solo, foi enterrado um conjunto equivalente de diferentes engenhos explosivos (minas terrestres, engenhos explosivos improvisados e munições não detonadas), variando nos seus materiais de revestimento (metal, plástico e madeira) e na sua profundidade de enterramento (5, 15 e 30 cm). Os varrimentos foram realizados paralelamente ao comprimento das áreas de estudo (9 m), com um espaçamento de 0.2 m (300 MHz) ou 0.4 m (100 MHz), aquando da utilização do 2D-GPR.

Os resultados obtidos permitiram verificar que o desempenho do 2D-GPR foi afetado por todas as variáveis estudadas. Apresentou a melhor capacidade de deteção aquando da utilização da antena de 300 MHz; nas estações com as melhores condições climatéricas (Primavera e Verão); nos varrimentos efetuados no solo do tipo argiloso (300MHz) ou arenoso (100MHz); na deteção de engenhos explosivos de metal e na deteção de engenhos enterrados a 15 cm de profundidade. Por sua vez, o 3D-GPR apresentou a melhor capacidade de deteção, tendo detetado todos os engenhos explosivos, independentemente das variáveis. A identificação dos engenhos não foi possível com nenhum dos GPRs.

Este trabalho de campo contribuirá futuramente para o desenvolvimento e standardização de protocolos de atuação para serem usados pelas forças policiais e militares, sempre que se depararem com situações reais em que exista a necessidade de deteção de engenhos explosivos enterrados, em solos nacionais, com vista à sua posterior inativação e remoção.

Palavras-chave: 2D-Easyrad; 3D-Radar; Geofísica Forense; IEDs; Solos/Sedimentos; UXOs.

ABSTRACT

During forensic investigations, the need of detecting buried objects that are possible related to occurred crimes (*e.g.* cadavers, arms, explosive devices) is common. Their search and detection need to be performed in the most cost-effective and rapid way, using non-destructive techniques. Geophysical methods seem to check all mentioned requisites, being the ground penetrating radar (GPR) regularly used for buried explosive devices detection.

With the present work it was intended the performance evaluation of two GPR systems to detect and identify different buried inert explosive devices, taking into account some contextual variables (frequency of GPR antenna; environmental conditions; soil type; type of explosive device casing material and their burial depth). Thus, GPR surveys were performed with the GPR 2D-Easyrad, using two antennas (300 MHz and 100 MHz), throughout a year (four seasons), with the devices buried in two soil types (sandy and clayey). In the Winter, a 3D-Radar was also used. In each soil type, a similar set of different explosive devices where buried (landmines, improvised explosive devices and unexploded ordnance) varying in their casing material (metal, plastic and wood) and in their burial depth (5, 15 and 30 cm). GPR scans where performed parallel to the study sites length (9 m), spacing 0.2 m (300 MHz) or 0.4 m (100 MHz), when using the 2D-GPR.

The obtained results allowed to verify that 2D-GPR performance was affected by all studied variables. 2D-GPR showed the best detection performance when using the 300 MHz frequency antenna; in seasons with the best environmental conditions (Spring and Summer); in scans obtained on the clayey soil type (300MHz) or on the sandy soil type (100MHz); in the detection of metal explosive devices and in the detection of explosive devices buried at 15 cm below ground surface. On the other hand, the 3D-GPR showed the best detection capacity, with all explosive devices being detected, regardless of the variables. Identification of the inert explosive devices was not possible with neither one of the two GPRs.

In the future, this field work will contribute to the development and standardization of suitable protocols of action for being used by the police and military forces, whenever they come across with real scenarios where there is a need to detect buried explosive devices, in national soils, aiming their latter inactivation and removal.

Keywords: 2D-Easyrad; 3D-Radar; Forensic Geophysics; IEDs; Soil/ Sediments; UXOs.

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ABBREVIATION LIST

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
AP	Antipersonnel
AT	Anti-tank
cm	Centimetres
DNA	Deoxyribonucleic acid
ED	Explosive device
EM	Electromagnetic
EMI	Electromagnetic induction
ERA	Electrical Research Association
ERW	Explosive remnants of war
GNR	Guarda Nacional Republicana
GPR	Ground Penetrating Radar
GHz	Gigahertz
GSSI	Geophysical Survey Systems Inc.
HE	High explosive
IED	Improvised explosive device
IPMA	Instituto Português do Mar e da Atmosfera
IR	Infrared
kJ/g	Kilojoules per gram
Km	Kilometres
LE	Low explosive
m	Metre
MHz	Megahertz
mm	Millimetre
N	North
ns	Nanoseconds
RAP	Rocket-assisted projectiles
S/m	Siemens per metre
S0	Zero survey
S1	First survey

S2	Second survey
S3	Third survey
S4	Fourth survey
Sc	Control survey
SPE	Sociedade Portuguesa de Explosivos
UN	United Nations
UXO	Unexploded ordnance
UWB	Ultra-Wide Band
W	West

I. INTRODUCTION

1.1. FORENSIC SCIENCES: GEOLOGY & GEOPHYSICS

1.1.1. FORENSIC GEOLOGY

In judicial cases, it is often necessary to appeal to experts, that have specific scientific knowledge, for the appreciation of certain evidence. The term “Forensic Sciences” refers to the application of sciences to Law issues, using valid and legal scientific methods (Magalhães and Dinis-Oliveira, 2016). Through the scientific analysis and interpretation of physical evidence found in a crime scene (*e.g.* fibres, DNA, fingerprints, hair, soil, documents), forensic sciences assist the law in solving mostly criminal, civil and labour cases, being, however, still inefficiently used on an international scale (Ludwig and Fraser, 2014).

Forensic Geology supports the law with the direct application of geological principles, proceedings and practices (Carvalho and Guedes, 2016). This science is manly dedicated to the characterization of geological matrixes like soils, sediments, rock fragments, minerals and fossils and to the study of the processes of their formation, being able to have many applications in a forensic context. Forensic Geology can act mainly by helping to establish the link between suspects and/ or objects to a crime scene; to locate clandestine graves and buried weapons; to detect adulteration of commercial products, and to investigate sources of environmental pollution (Pye, 2007). However, human activities involving house constructions and manufacturing, have led to geological materials transportation and consequent Earth’s natural surface modifications, existing few areas unaltered, which result in more complex forensic geology investigations. Thus, forensic geologists take advantage on working in a multi-disciplinary way, integrating methods and knowledge of other disciplines and sub-disciplines, including scientific and social sciences (Fig. 1).

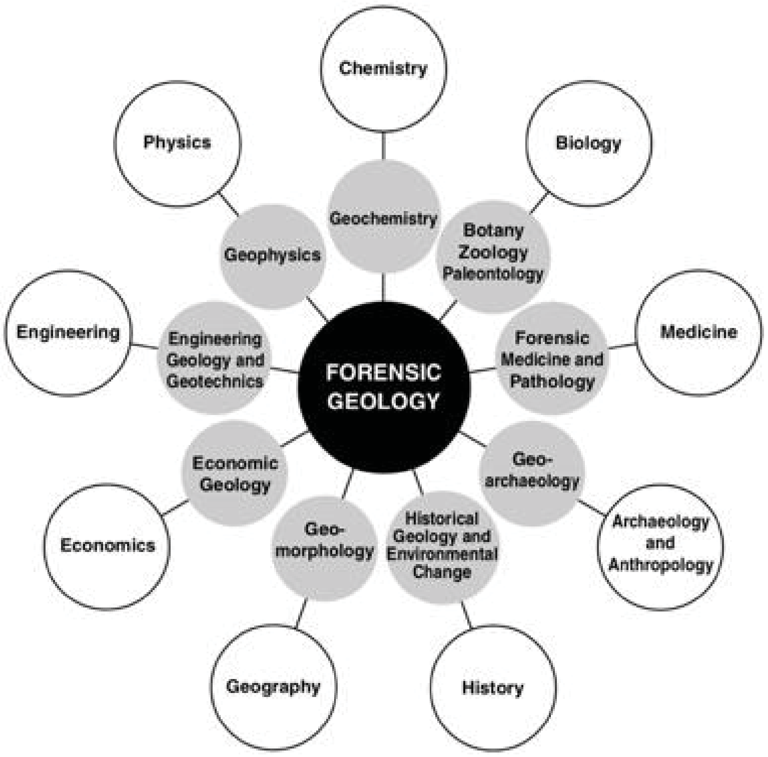

Figure 1. Inter-disciplinary work between Forensic Geology and other disciplines and sub-disciplines (source: Pye, 2007).

Two of the main analysed geological evidence are soil and sediment samples. The formation of soil occurs through a combination of physical, chemical and biological processes affecting a geological parent material, *in situ* (Verheye, 2009), resulting in layers of unconsolidated material. A wide variety of different soil types can be encountered along the Earth's surface, with great spatial variation in terms of their biological, chemical, mineralogical, hydrological and physical properties (Fitzpatrick, 2013), as a result of the interaction between several factors: geological parent material, climate, topography, biological influences and time (Jenny, 1941; Pye, 2007). When a mixture of loose particles, resulting from the previous mentioned processes applied to one or more geological parent materials, are transported mainly by air or water, being deposited in another place (*e.g.* beaches), sediments are formed (Pye, 2007). These geological substrates are basically consisted of inorganic and organic materials, water and gases (McNeill, 1980), being often classified in terms of particle size, based on their percentages of sand (0.063 to 2.00 mm), silt (0.004 to 0.063 mm) and clay (0.002 to 0.004 mm) (Pye, 2007).

Soil is known as a contact trace, being mostly used to help linking a suspect to the scene of a crime. Fitzpatrick (2013) enumerated six characteristics that make soil a powerful contact trace: soil is highly individualistic (diversity/ heterogeneity); soil has a high probability of being transferred and retained; soil is nearly invisible; soil can be quickly collected, separated and concentrated; soil materials are easily characterized and, luckily, computerized soil databases exist. Besides that, soil is ubiquitous and an integral part of both terrestrial and aquatic environments (Fitzpatrick, 2013). Contributing to the soil uniqueness, anthropic objects/ particles are usually found in modern soil and sediments, being also of interest to a forensic geologist (Carvalho and Guedes, 2016; Pye and Croft, 2004). The use of geological evidences in forensic investigations and court, has been gradually increasing due to the awareness of their potential by professionals and public (Pye and Croft, 2004).

1.1.2. FORENSIC GEOPHYSICS

As previously referred, during forensic investigations it may be necessary to find clandestine graves or illegally buried forensic objects like weapons, drugs and explosive devices, to effectively persecute someone. This need is usually fulfilled through large-scale ground searches and excavations, which can be expensive, manpower intensive, non-productive and that can lead to criminal evidence destruction (Pye and Croft, 2004). Geophysical methods, implemented throughout the years, have been an asset to forensic investigations (Pringle *et al*., 2012), by providing alternative non-invasive, non-destructive, rapid and cost-effective methods for ground search (Pringle *et al*., 2008).

Geophysics applies physical principles to study the Earth's physical properties, through the analysis of measurements that are taken at or near the surface of the Earth (Kearey *et al*., 2002). There is a number of different geophysical methods that analyse different soil physical properties (Pye and Croft, 2004), measuring their variations regarding background readings, to find anomalies that could correspond to potential forensic buried objects. Pye (2007) pointed out the main geophysical methods that are used in forensic investigations: shallow seismic reflection profiling; gravity surveys; magnetic anomaly surveys; resistivity surveys; electromagnetic conductivity profiling; metal detector surveys and ground penetrating radar (GPR) surveys (Buck, 2003; Fenning and Donnelly, 2004; Milsom, 2003; Nobes, 2000; Pringle *et al*., 2012; Richardson and

Cheetham, 2013; Ruffell and McKinley, 2005; 2008). These can be used individually, however, the use of multi-sensor techniques, where different methods are combined, is much more preferable.

Besides knowing the capabilities of the geophysical methods, for a good selection of which to use, it is also essential to know their limitations, some pointed out: presence of man-made metallic and non-metallic features at and below the ground surface under analysis, since they can lead to false positives; ground irregular topography; access problems; seasonal unfavourable factors (*e.g.* weather), and electrical interference (MacDougall *et al*., 2002). Thus, the selection of the most appropriate geophysical method to achieve a successful ground search will depend, mostly, on the chemical and physical properties of the ground, the site conditions, the size of the target/ search area, as well as the constitution and burial depth of the targets (Dionne, 2007; Ruffell and McKinley, 2008).

1.2. GROUND PENETRATING RADAR: THEORETICAL CONTEXT

1.2.1. BACKGROUND

The first patent created in radar technology is associated with Christian Hulsmeyer in 1904 (Patent DE 165 546). Only six years later, in 1910, a patent was filled by Gotthelf Leimbach and Heinrich Lowy, for the rights to use the radar technology to locate buried objects (Patent DE 237 944). Later, in 1926, Hulsenbeck requested a patent for the use of pulse radar systems (Patent DE 489 434), or antenna technology, leading to an improvement in image resolution. In 1929, W. Stern used the technology of ground penetrating radar, through radio-echo-sounding, to determine a glacier ice thickness, being one of the first works made with GPR (Milsom, 2003; Sahni *et al*., 2014). However, it was only in 1934 that the term “Radio Detection And Ranging” (RADAR) emerged, being applied to all equipment used to detect objects and their distance from the source, through radio waves emission (Buderi, 1996). This technique lost some interest until the early 1970s, when GPR systems started to be developed mostly for military applications (Sahni *et al*., 2014). Since then, the range of developed systems and applications has been steadily increasing (Jol, 2009), arousing special interest in the last decades to the search of objects buried beneath the shallow earth surface (Chantasen *et al*., 2018).

The first commercial GPR was manufactured by Geophysical Survey Systems Inc. (GSSI), in 1974 (Morey, 1974), the leading manufacturer of GPR systems. During 1990’s, the interest on GPR technology was really enhanced, leading to important GPR progresses like the development of multi-fold data acquisition and digital data processing (Annan, 2002). During this period, commercial products especially designed by “The Electrical Research Association” (ERA) for unexploded ordnance (UXO) and landmine detection, became available (Annan, 2002).

GPR is nowadays a widely used geophysical technique, being recognized by its many applications in, for example, utility mapping, road inspection, geology, archaeology, engineering, military and forensics. This technique has also already proved to be effective in detecting metallic and non-metallic landmines, buried in different soil types (Chantasen *et al*., 2018; Tesfamariam and Mali, 2012).

1.2.2. FUNDAMENTAL PRINCIPLES

1.2.2.1. PRINCIPLES OF OPERATION

GPR is an active geophysical method that uses the propagation of electromagnetic (EM) radiation through a given medium (*e.g.* soil, concrete), employing high frequencies that can go from 100 MHz up to 100 GHz, allowing the formation of high-resolution images of the subsurface (Bhuiyan and Nath, 2006).

The radar technology operation is based on emission of EM waves from a transmitter antenna that, while propagating in depth, can encounter contrasting electromagnetic properties as a result of subsurface heterogeneities (*e.g.* soil interface, rocks, pipe, buried mine, cadaver) with distinct dielectric properties from that of the surrounding medium (Assunção, 2016). The result is then refraction of a fraction of these waves that continue to travel downward, while the rest is reflected back to the surface, being detected by the receiver antenna. The data are then recorded and stored into a digital device, being able to be displayed and visualized in real time (Daniels, 2000; Fig. 2). However, for a correct data interpretation, several number of processing techniques need to be applied later, contributing to the enhancement of the hyperbolic-shape target signals and elimination of non-target signals (clutter or background noise).

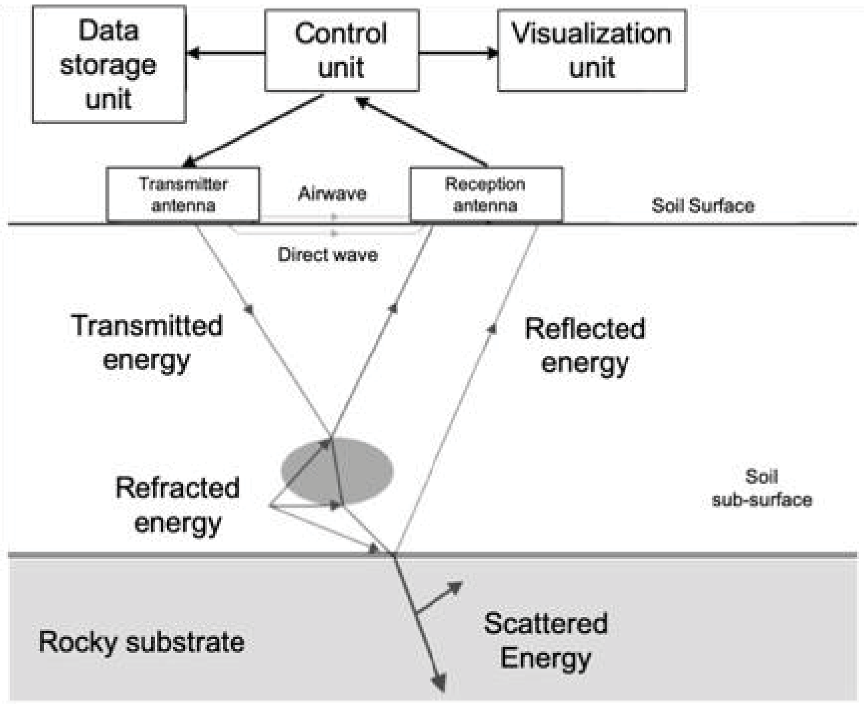

Figure 2. Schematic representation of the components and principles of operation of an ordinary GPR system. (source: Gonçalves, 2013).

Two distinct types of GPR exist: time-domain and frequency-domain. In the time-domain the EM energy is emitted as an impulse, and the reflected signal is processed with a sample receiver that record the variations with time (Lopera *et al*., 2007). This GPR type can be further divided into Impulse System GPR, that emits a pulse with a carrier frequency, and Ultra-Wide Band (UWB), which emits the pulse without a carrier frequency, resulting in emitted energy with very large spectral band (Bhuiyan and Nath, 2006). When the GPR is operated in the frequency-domain, the energy is transmitted in a sequential manner as individual frequencies (swept frequency), and it is received with a frequency conversion receiver (Daniels, 2009) that converts data to time-domain.

GPR systems can be designed to work as hand-held or vehicle-mounted (Witten, 1998) depending on the study requirements. A hand-held GPR can be carried by a single person and it is better to reach places of difficult access by vehicles, whilst a vehicle-mounted system is much more efficient in large areas, allowing a more rapid survey of all test site (Tesfamariam and Mali, 2012). Furthermore, a GPR system can be operated near or far from the ground surface (Daniels *et al*., 2008). The fact that GPR equipment get to be operated without touching the ground surface is a huge advantage in demining operations due to the presence of explosive devices that can be activated by pressure (Fachbereich, 2013), while also improving the detector mobility (Scheers, 2001).

While the system is moved along the ground surface, the data of the shallow subsurface are collected uninterruptedly. The collected data can be presented in three distinct formats, depending on the number of surveying dimensions: A-scan, B-scan and C-scan (Bhuiyan and Nath, 2006). The A-scans, or 1-D time signal/ trace, are represented by the amplitude of the signal in function of time for a single ground position (Lopera *et al*., 2007). When the GPR is moved along a straight line parallel to the ground surface, A-scans are sequentially recorded for each position, leading to the formation of 2-D cross sections, or B-scans (radargrams). Radargrams, acquired along the whole test site through adjacent straight parallel lines, can be then combined forming a 3-D visualization, or C-scan (Kadioglu and Kadioglu, 2016).

The success of a ground subsurface study with the GPR will depend mainly on the chosen frequency of operation, the medium and environmental characteristics, the level of signal attenuation, the object/ material's physical characteristics and the depth penetration and image resolution intended (Assunção, 2016; Schubert and Kuznetsov, 2002).

1.2.2.2. GROUND PENETRATING RADAR ANTENNAS

The antennas are probably the most important component of a GPR system, being mainly designed to optimize the surface - system interaction (Costa, 2009), needing to be carefully chosen to achieve the best possible GPR performance.

GPR systems can be designed to work with two separate antennas (transmission and receiving), which is known as a bistatic system, whilst sometimes, only one antenna works as a transmitter and a receiver of EM waves, being called a monostatic system (Daniels, 2000). In a bistatic system, during surveys, the transmission and receiving antennas may be fixed or be in motion, with the same or different spacing between them. These are called surveying modes, which can be of four types (Fig. 3): common source, common receiver, common offset and common depth/point. In common source and common receiver, the transmitter and receiver antenna, respectively, are fixed, while the others move along the survey direction. In the case of common offset both antennas are moved along the survey direction with fixed spacing between them at each measurement location, while in common depth/ point the antennas are moved in opposite directions, away from a common point (Fachbereich, 2013).

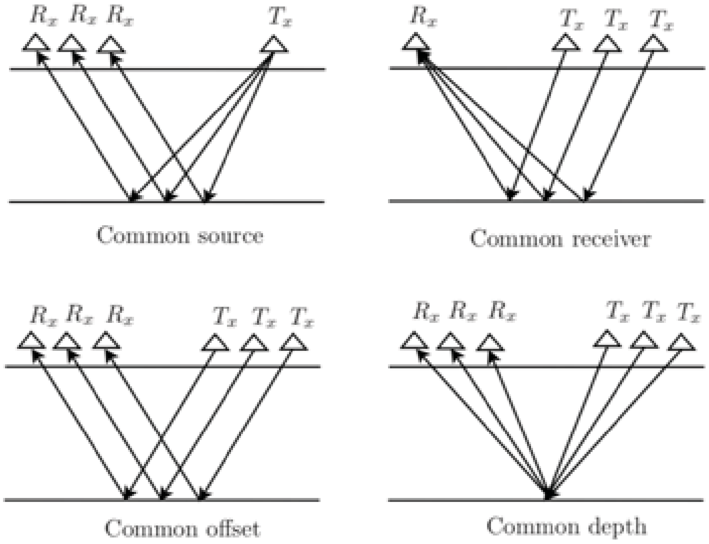

Figure 3. Surveying modes of a GPR survey. (Rx-reception antenna; Tx-transmission antenna; source: Fachbereich, 2013).

The bandwidth and centre frequency are the most important parameters to take into account when choosing the antenna to be used, since it is going to define, along with other factors, the depth of penetration and the image resolution (Table 1). Therefore, higher frequencies will allow for a better image resolution, however, the EM waves will suffer more attenuation, leading to shallow depth penetration. On the other hand, lower frequencies allow an increase in depth penetration, however, decreasing the resolution (Schultz *et al.*, 2013). Thus, it is important to know which are the survey goals, what is the likely target to be detected and the conditions of its burial, as well as the soil properties (Scheers *et al.*, 1998), so that a proper choice of antenna frequency can be made, being always necessary to reach a commitment between depth of penetration and resolution (Fachbereich, 2013). Taking as an example the detection of buried landmines, an antipersonnel (AP) mine (diameter of few centimetres) is usually buried at shallow depths, so, it is normally recommended the use of higher frequencies (Yarovoy *et al*., 2001), since resolution is more important than depth penetration. However, explosive devices can also be found at greater depth due to soil movement (Daniels, 2009), thus being necessary a lower frequency.

Table 1. Typical penetration depth for dry sandy soils and signal resolution for different GPR antenna frequencies (source: Gonçalves, 2013).

Antenna centre frequency	**Depth of penetration (metres)**	**Qualitative Resolution**
100 MHz	15	Low
200 MHz	10	Low to Medium
270 MHz	6	Medium
400 MHz	4	Medium to High
900 MHz	1	High
1000 MHz	0.5	High
>1500 MHz	0.4 – 0.5	Very High

Furthermore, an incorrect antenna - ground surface coupling, usually during surveys on terrains with uneven and irregular soil surface and high vegetation, may be associated with the increase of energy losses, since part of the emitted energy cannot be effectively transmitted into the soil, contributing to a consequently enhancement of electromagnetic waves attenuation (Assunção, 2016; Gonçalves, 2013).

1.2.2.3. ELECTROMAGNETIC PROPERTIES OF MATERIALS

The GPR technology can detect the presence of a buried object due to the contrasting electromagnetic properties between features and the surrounding medium, being the most important the permittivity or dielectric constant (ε) and the electrical conductivity (σ) (Woods, 2011), which will affect the propagation of the electromagnetic waves by influencing their level of attenuation and velocity. The greater the contrast between EM properties, stronger the reflected signal, resulting in an easier detection (Griffin and Pippett, 2002). Both properties are mostly affected by the moister content of the medium (Sato, 2009), which will lead to their increase, leading to changes in wave propagation. In Table 2, values of relative dielectric permittivity, conductivity and propagation velocity of EM waves are represented, for a variety of possible environments.

Table 2. Different environments and values of their dielectric constant, electrical conductivity and propagation velocity (source: www.easyrad.com.ua; Assunção, 2016; Gonçalves, 2013).

Environment	**Relative Dielectric Permittivity, ε_r**	**Electric Conductivity, σ [mS/m]**	**Propagation Velocity [m/ns]**
Air	1	0	0.3
Distilled Water	80	0,01	0.033
Fresh Water	80	0.5	0.033
Sea water	80	3000	0.01
Ice	3 - 4	0.01	0.16
Dry sand	3 - 5	0.01	0.15
Saturated sand	20 - 30	0.1 - 1	0.06
Limestone	4 - 8	0.5 - 2	0.12
Shale Clay	5 - 15	1 - 50	0.09
Silt	5 - 30	1 - 100	0.07
Clay	5 - 40	2 - 200	0.06
Granitic Rock	4 - 6	0.01 - 1	0.13
Dry sandy soils	4 - 6	0.1 - 100	0.12 – 0.15
Saturated sandy soils	15 - 30	10 - 100	0.05 – 0.08
Dry clayey soils	4 - 6	0.1 - 100	0.12 – 0.15
Saturated clayey soils	10 - 15	10 - 1000	0.08 – 0.09

The majority of the natural materials present on Earth are considered dielectric materials, which means that when submitted to an external electric field they store energy (Baker *et al*., 2007) and allow the propagation of an electromagnetic field. The permittivity value of a material describes its ability to store and release electromagnetic energy when subjected to an external electric field. A material is commonly characterized by its relative dielectric permittivity (ε_r), that is a dimensionless value. This is the main property that determines the velocity at which EM waves travel in the subsurface, decreasing with the increase of relative permittivity value (Daniels, 2000; Giannopoulos, 2005; Nambiar *et al*., 2017). Knowing the permittivity of the propagating medium, can be essential to know the propagating velocity of EM waves and, consequently, determine the depth of a target (Griffin and Pippett, 2002; Sato *et al*., 2004).

The electrical conductivity value, measured in S/m (Siemens per metre), represents the ability of a material to pass free electric charges, through electron movement, in response to an external EM field (Woods, 2011), being a measurement of the concentration of ions in solution (Pye, 2007). This property controls the amplitude and attenuation of the EM waves (Baker *et al*., 2007). Electrical conductivity varies greatly between soils and even in the same soil, being mainly dependent on porosity, moisture content, material composition and temperature (McNeill, 1980). The presence of clay particles and soluble salts on soils also influence their electrical conductivity, increasing it (McNeill, 1980), thus, significantly decreasing the depth penetration of the EM waves. This is due to an elevated quantity of conductive electrons and ions that quickly dissipate radar energy, leading to completely attenuation of EM waves in soils with high clay content and saline conditions (Jol, 2009), exponentially arising with depth. On the other hand, in fresh water conditions and ice, GPR surveys are shown to be feasible (Daniels, 2007).

1.3. EXPLOSIVE DEVICES

An explosive is characterized as a substance, or a mixture of substances, usually an oxidizing and a reducing agent, that works by liberation of large quantities of energy (kJ/ g) and hot gasses, in a short period of time, due to a rapid chemical change (Siegel *et al*., 2013).

Explosives can be legal used by industry/ military, or illegal used in criminal/ terrorist attacks, being their variety classified according to their chemical structure, use and explosive properties (Siegel *et al*., 2013). Therefore, an explosion may be of three different types: chemical, mechanical or nuclear. Furthermore, the explosive material used to accomplish a chemical explosion can be classified as a low or high explosive, which will vary in their uses and effects. Whilst a low explosive (LE) deflagrates or burns at a very high speed to provoke the release of tremendous amounts of gasses, high explosives (HEs) will detonate, enhancing the destruction power. HE can be further classified as primary, secondary and tertiary (Laska, 2016). Generally, buried munitions and explosive devices can be divided in three main groups: landmines, improvised explosive devices (IEDs) and explosive remnants of war (ERWs), which includes the unexploded ordnance (UXO) (Faust *et al*., 2011).

Landmines are designed to damage vehicles and/ or kill/ wound or just restrict people's activities, being grouped in two general categories: Anti-Tank (AT) mines and Anti-Personnel (AP) mines. They can be usually encountered buried, hidden in grass or buildings, and even fixed on stakes or to trees, being possibly activated by pressure, tripwires, command detonation, time, or a combination of these methods (UNMAS, 2015).

The commonly known "bombs" or IEDs, usually used in terrorist attacks, are explosive devices that have been modified, by joining them with home-made components (*e.g.* screws, shrapnel), with the aim of increasing their explosive/ destruction power. These type of explosive devices, besides the additional home-made components, require an explosive and an initiation system which can be of three types: time, victim or command initiation (Siegel *et al.*, 2013).

An ERW is considered as a munition, or an element of one, that was removed from a field belonging to previous or current war zones (Gersbeck, 2014). UXOs can include artillery, mortars, fuses, grenades, rockets and/ or missiles, being defined as ordnance that was deployed on the ground with a specific purpose but were not able to function as designed (UNMAS, 2015). Also, dangerous and unpredictable munitions, due to damage by explosions or other source of harm, should be considered as UXOs.

The identification of an ordnance before its removal, is important to guarantee that appropriate safety precautions are applied, varying between different munitions (Gersbeck, 2014).

1.3.1. BURIED EXPLOSIVE DEVICES: A HUMANITARIAN PROBLEM

Buried explosive devices have constituted a humanitarian problem throughout the years, leading to high number of civilian victims, nearly half of whom are children. The "1997 Convention on the Prohibition of the Use, Stockpiling, Production and Transfer of Anti-Personnel Mines and on their Destruction", commonly known as the Ottawa Treaty, accounted in 2018 for a total of 164 states, including Portugal, who had signed/ ratified/ acceded it, contributing with resources towards mine clearance and other mine action activities (ICBL-CMC, 2018). The annual Monitor recorded, in 2017, 7.239 landmines/ ERW casualties in 49 countries, with 2.793 killed people, and the highest numbers in Monitor history for annual fatalities caused by IEDs (2.716) and for child victims (2.452). Since the beginning of this global tracking in 1999, more than 122.000 mine/ ERW casualties were recorded, including some 86.000 survivors.

In terms of contamination and clearance, it is believed that in 2018 sixty states and areas are still contaminated by antipersonnel mines, with two-thirds of the previous contaminated states/ areas clear. The process of demining is very challenging and can be accomplished with different techniques, the most common being prodders, metal detectors and biological detectors (*e.g.* dogs, pigs, rats), which although efficient, show a lot of drawbacks (Tesfamariam and Mali, 2012). These demining operations are also very dangerous for the deminers, killing two for every 1.000 removed mines, as stated in the statistics of the United Nations (UN) (Núñez-Nieto *et al*., 2014). The technology of GPR, together with other sensor technologies, like electromagnetic induction (EMI) and infrared (IR) (Bhuiyan and Nath, 2006; Sun *et al*., 2005), has been developed with the aim of improving the success and security of the demining operations, being actively applied to landmine detection for nearly 20 years (Tesfamariam and Mali, 2012).

Explosive devices can be found everywhere, from desert regions, mountains, jungles, to urban areas, in different environmental conditions, being buried at different depths, or even just placed on the surface. These diverse conditions contributes to the challenging work of finding feasible techniques that can detect them (Daniels, 2009).

II. AIMS

Ground Penetrating Radar (GPR) has been gaining a lot of relevance throughout the years, being now an established technology for explosive devices detection. Despite having some limitations, like being interfered by the presence of roots, rocks and other natural clutter, as well as difficulties in operating in extremely moist or dray environments, it has been successfully used in a wide range of soil types and environmental conditions and can detect both metallic and non-metallic targets (MacDonald *et al.*, 2003), which is very important due to the crescent number of minimum metal and plastic mines.

A lot of works has been published concerning a lot of sophisticated radar methods for explosive devices detection and processing techniques. However, when they are moved from the laboratory to the field, few of them proved to be reliable (Daniels, 2009). Thus, the equipment used for buried explosive devices detection needs to work in a wide range of soil and climatic conditions (Fachbereich, 2013). Field studies, like the one presented in this work, encompass these variables, being extremely important for testing the feasibility of GPR systems in practical studies that are more similar to real scenarios. Thus, the main aim of this work is to test the feasibility of buried inert explosive devices detection using GPR technology towards five variables:

- Antenna frequency;
- Environmental conditions;
- Soil type;
- Explosive device casing material;
- Burial depth.

Furthermore, the present work also aims to evaluate the difference in detection capability of a 2D and a 3D GPR system.

Obtained results can then be used to develop suitable standardized protocols, able to assist the Portuguese police and military, if they come across the need of detecting buried explosive devices in national soils.

III. MATERIALS AND METHODS

3.1. FRAMING OF GPR'S TEST SITE

3.1.1. GEOGRAPHIC AND GEOLOGICAL CONTEXT

The test site for the present work was carefully chosen due to the need of having a controlled and protected location to handle inert explosive devices, loaned by the Guarda Nacional Republicana (GNR), burying them, at least, for one year. thus, this work was performed at a facility of the Military Unit of Serra do Pilar, a former Artillery Regiment Unit in Vila Nova de Gaia, Porto. The city of Vila Nova de Gaia, composed by 24 parishes, is located in the south zone of Porto metropolitan area, being limited west by the Atlantic Ocean and north by the Douro River. The average annual temperature of the city, based on readings from 1971 to 2000, made on Serra do Pilar weather station (41°08'N, 08°36'W, 93m), is 14.7°, being the average annual precipitation of 1253.5 mm (Instituto Português do Mar e da Atmosfera (IPMA)).

Within the test site, two study sites were chosen, one with a sandy soil and another with a clayey soil, being important to notice that the sandy soil was, in a distant past, anthropically placed into a cement box, in order to be used for military sports.

3.1.1.1. GEOGRAPHIC CONTEXT

The facility of the Military Unit of Serra do Pilar (41°14'N, 08°60'W) is located in an urbanistic area, in Santa Marinha e São Pedro da Afurada riverside parish. It is limited north by the Gonçalves Zarco street, west by the Alameda da Serra do Pilar and east by the Avenida Dom João II. It is also about 200 metres and 400 metres south of the Geophysical Institute of Porto University and of the Douro River, respectively.

The location of the test site is included in the extract of the 122 – Porto sheet of the Portugal´s Military Letter at 1:25.000 scale, of the Army's Geographic Institute (Fig. 4).

Figure 4. Test site in the facility of Military Unit of Serra do Pilar, Vila Nova de Gaia, Porto (blue circle) indicated in the extract of the 122 – Porto sheet of Portugal's military letter of the Army's Geographic Institute, at 1:25.000 scale.

3.1.1.2. GEOLOGICAL CONTEXT

Vila Nova de Gaia is highly represented by Precambrian and Archaic metamorphic lands, being the most ancients those from the ante-Ordovician schist-graywacke complex, which occupy 58% of the Vila Nova de Gaia territory, including the test site. This complex is essentially formed by fine mica schists and metagraywacke formations, the rocks appearing usually cut by granitic material. Occupying large areas of Vila Nova de Gaia, including Santa Marinha e São Pedro da Afurada parish, are also migmatites, gneisses, mica schists and light schists, resulting from rock intense metamorphism.

The location of the test site is included in the extract of the 13A – Espinho sheet of the Portugal´s Geologic Letter at 1:50.000 scale, of the Geologic Services (Fig. 5).

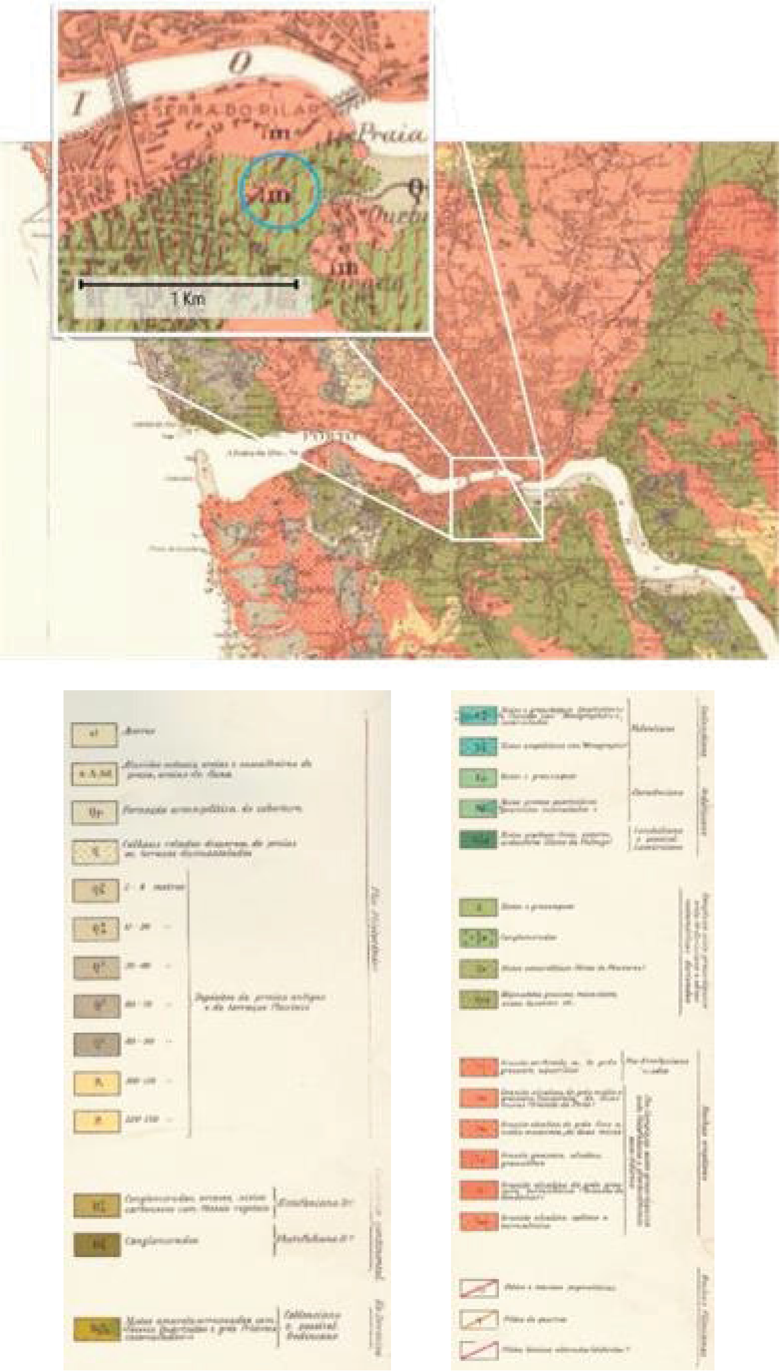

Figure 5. Test site in the facility of Military Unit of Serra do Pilar, Vila Nova de Gaia, Porto (blue circle), indicated in the extract of the 13A – Espinho sheet of Portugal's Geologic letter of the Geologic Services, at 1:50.000 scale.

3.2.1. GROUND PENETRATING RADAR (GPR) EQUIPMENTS

3.2.1.1. 2D-EASYRAD

The 2D-Easyrad Ground penetrating radar (GPR) (Fig. 6) has a maximum frequency bandwidth of 10 MHz to 800 MHz, depending on the used antenna, and a time window of 75 or 150 ns, which determine how deep the radar system will investigate the subsurface (Sahni *et al*., 2014). This GPR has bi-static antennas, which means that the receiver and transmitter antennas are separated and linked to a reception and transmission units, respectively. Furthermore, it has a battery and it is linked to a control unit (*e.g.* tablet), where the acquisition parameters are defined, and data are stored and visualized. The middle point between the antennas (0.6 m), represents the point of data acquisition.

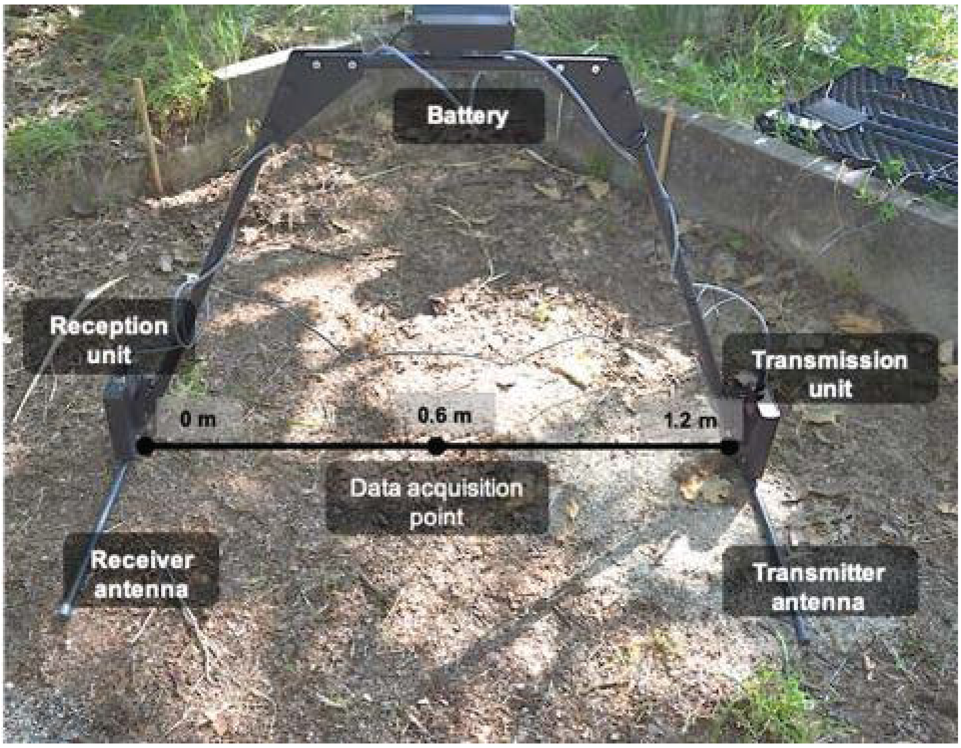

Figure 6. 2D-Easyrad ground penetrating radar.

In the present work, the used form of GPR surveying was the common offset mode, which is the most broadly used surveying mode (Jol, 2009; Milsom, 2003). The used GPR system has a hand-held operation, and the antennas are moved in a straight line near the surface of the ground, functioning as air-coupled antennas. The antennas are not shielded, which makes them vulnerable to clutter from direct coupling and interference from the surrounding environment (*e.g.* trees, cables).

Due to the soil types of the present work, the type of targets, the depth of their burial, and the study purposes, it was chosen an antenna with a central frequency of 300 MHz (Fig. 7), being the higher frequency available. An antenna with a central frequency of 100 MHz (Fig. 7) was also used, at the Spring and Autumn surveys, for comparison purposes between two different frequency antennas. Both antennas can have a frequency coverage of 10 MHz up to 500 MHz (Oerad, 2018).

Figure 7. 2D-Easyrad ground penetrating radar antennas of different frequencies (300 MHz above; 100 MHz below).

3.2.1.2. 3D-RADAR

The 3D-Radar (Fig. 8) offers a wide frequency range, varying from 100 MHz up to 3 GHz, enabling optimization towards different study objectives. Its system uses a step-frequency technique, an innovative way of radar signals collection, being the GeoScope (data collection system), coupled to a distinctive multi-channel antenna array of 1.8 metre wide, containing 23 pairs of antennas, allowing the production of 23 parallel GPR profiles in a single line scan. This antenna array can be elevated from the ground surface, at highs up to 50 cm, enabling high-speed surveys.

Comparing with a traditional impulse based GPR, the use of a step-frequency technique enables an easy consecutive incremental of frequency during a subsurface survey, from low to high, not being necessary the use of multiple antennas operating at separate frequencies ((3D-Radar, 2009); Fig. 9).

Figure 8. 3D-Radar.

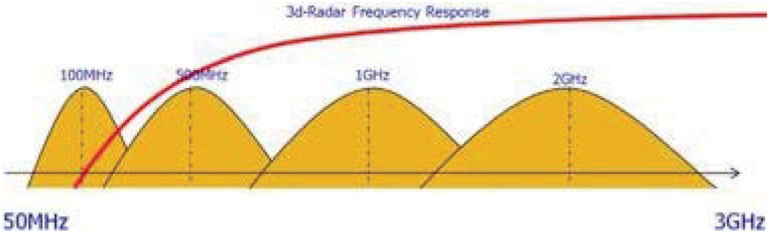

Figure 9. Schematic representation of the frequency range coverage by the step-frequency technique (red line), compared with the need of multiple frequency antennas in a traditional impulse based ground penetrating georadar (source: 3D-Radar, 2009).

3.2.2. BURIED TARGETS

Within the test site of the present work, there were two study sites with different soil types, a sandy soil and a clayey soil, where two similar sets of inert explosive devices (Fig. 10) were buried. The explosive devices were provided by the GNR – Destacamento de Intervenção do Porto and included: two plastic antipersonnel (AP) mines (1), two improvised explosive devices (IEDs) in a plastic box (2), two IEDs in a wooden box (3), two instruction hand grenades Mod/962 (4), two MILLS hand grenades (5), two rockets (6), two 81 mm mortar grenades (7), two 155 mm artillery projectiles (8), one 80 mm artillery projectile (9), one 60 mm artillery projectile (10), one 101 mm artillery ammunition case (11), one 105 mm artillery ammunition case (12) and one FIREND (13). Besides the explosive devices, raw chickens (14) were also buried, representing organic controls and holes were open in the ground, being afterwards filled with the same withdrawn soil, representing negative controls (disturbed soil only).

Figure 10. Targets buried in the sandy soil study site (a) and in the clayey soil study site (b): (1) antipersonnel mines; (2) improvised explosive devices in a plastic box; (3) improvised explosive devices in a wooden box; (4) Instruction hand grenades Mod/962; (5) MILLS hand grenades; (6) rockets; (7) 81 mm mortar grenades; (8) 155 mm artillery projectiles; (9) 80 mm artillery projectile; (10) 60 mm artillery projectile; (11) 101 mm artillery case; (12) 105 mm blank M365 cartridge case; (13) FIREND; (14) chicken.

Antipersonnel (AP) mines are weapons normally activated when a person gets in contact or gets close to them. Compared with the anti-tank (AT) mines, the AP mines are smaller and have less explosive content. They are formed by an explosive, a detonator, a spring, a casing and a void (MacDonald *et al.*, 2003) and can appear in many different shapes and materials (wood, plastic or metal). The AP mines used in the present work have a cylinder-type shape and a plastic casing (Fig. 11).

Figure 11. Plastic anti-personnel mine with a cylinder-type shape.

An IED is an explosive device formed with additional manmade components, used to enhance the destruction capability of the ordnance. In the present work two IEDs were used, differing in their casing, being one inside a wooden box (Fig. 12a) and the other inside a plastic box (Fig. 12b).

Figure 12. Improvised explosive device (IED) a) in a wooden box, and b) in a plastic box.

Hand grenades were invented in the early 10th century by the Chinese, being known as one of the first forms of explosive devices to be used in warfare. The first hand grenades were made by clay, bamboo segments or tarred paper, filled with gunpowder and sealed with wax. In Europe, they only started to be used in the mid 15th century (Pegler, 2004). They can function as defensive or offensive grenades and are usually constituted by a fire artifice, a bursting charge and the grenade body. Hand grenades are easily found outside military control, due to their small size and huge manufactured number (Gersbeck, 2014). Some hand grenades used in the present work, were the Mod/962, that was made by the Sociedade Portuguesa de Explosivos (SPE). This type of grenades has different versions, being distinguished by their colour. Thus, the green hand grenades work as a high explosive; the blue hand grenades (used in the study; Fig. 13a) are filled with sand being only used for practice, and the grey hand grenades release smoke or tear gas.

Other type of hand grenades that were also used in the present work were the MILLS hand grenades (Fig. 13b), defensive grenades that were firstly produced in 1915, by William Mills, becoming the first British hand grenades to be issued on a mass scale (Pegler, 2004). This type of grenade has an external segmented body to enable a better grip and was designed to fragment into small particles.

Figure 13. Hand grenades: a) Instruction Mod/962 and b) MILLS.

Rockets (Fig. 14), or rocket-assisted projectiles (RAP), are self-propelled devices that contain a small rocket motor in the rear, which allows them to achieve great travel distances. They are launched by rocket launchers, that can be consisted by a single tube, launching a single rocket, or be consisted by a dozen of tubes, enhancing the destructive power. They were first used by the British Royal Navy in the early 19th century, and then, during the Second World War, a significant number of rockets were also used by Russian and German forces (Dullum, 2010). For decades, largest quantities of artillery rockets were part of the inventories of non-state armed groups, mainly due to its easy and safe way of operation (Schroeder, 2014). These weapons vary greatly in terms of size, calibre, range, technological sophistication and role (Dullum *et al*., 2017).

Figure 14. Rocket grenade.

Mortars are curved shooting weapons with soil absorbed recoil and preload loading, which are their two main distinctive characteristics. The first mortar was created in 1915 by Wilfred Stokes. They are weapons relatively simple to manufacture and operate, since are portable, cheap and versatile, which contributes to their frequent employment in current and recent conflict zones, being used by almost all military forces (Dullum *et al*., 2017).

Mortars can be divided into four broad categories regarding their calibre, each with specific applications: light (up to 65 mm), medium (70 to 90 mm), heavy (100 to 120 mm) and extra-heavy (above 120 mm). The munition used by the 81 mm mortar can be of three types: high explosive (HE), smoke, illuminating and practice. The ,type is mainly distinguished by its colour painting and colour marks (Government, 2015). In the present work it was used a medium calibre mortar of 81 mm (Fig. 15), being a practice type projectile, since it is painted in blue with white marks.

Figure 15. Mortar grenade (81 mm).

A projectile is a part of an artillery munition, being the component that reaches the intended target. It is normally formed by the projectile body, the fuse, the bourrelet, the rotating band and the high explosive that detonates upon impact or at previously programmed heights. In the present work it was used three different projectiles, differing in their calibres: 155 mm (Fig. 16a), 80 mm (Fig. 16b) and 60 mm (Fig. 16c).

The artillery guns of 155 mm calibre were originally developed in France. They are considered “heavy artillery”. Their projectile can weight approximately 40 kg and have ranges of 17-40 km (GICHD, 2017). 155 mm artillery projectiles have been used in many army conflicts, including those in Qana, Lebanon (18 April 1996), Gaza, Palestine (24-29 July 2006) and Jabaliya Girls Elementary School A & B, Gaza, Palestine (30 July 2014).

Not much bibliography is available about the 80 mm and 60 mm artillery projectiles. However, it is known that the 80 mm artillery field gun appeared in 1877 in France, designed as a lightened version than the previous existent artillery systems, so it could be used within cavalry divisions.

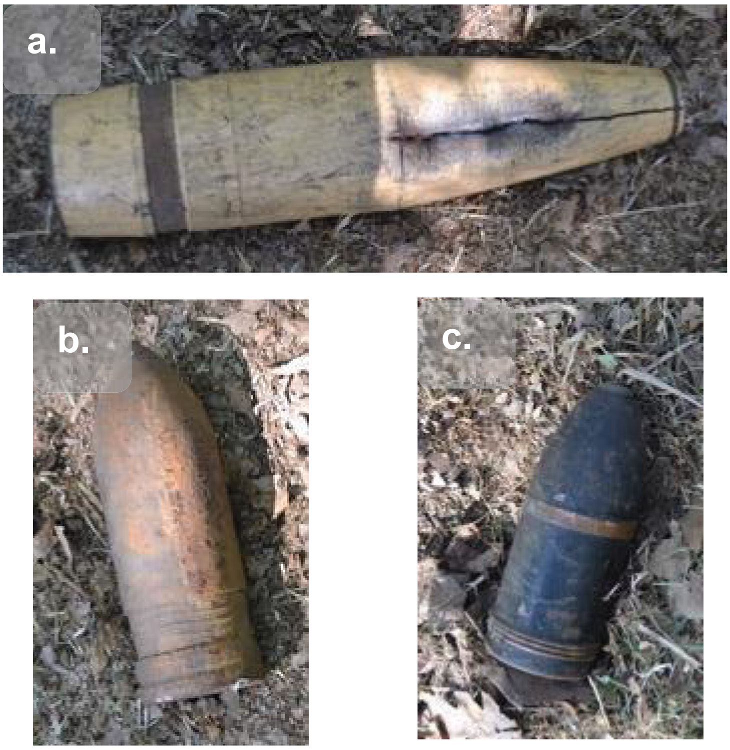

Figure 16. Artillery projectiles: a) 155 mm, b) 80 mm and c) 60 mm.

The cartridge case is part of an artillery ammunition, serving as the container of the propelling charge, being possibly made of steel, brass or a combustible material. In the present work, it was also buried two different cartridge cases, one in each soil type: a 101 mm artillery case in the sandy soil (Fig. 17a) and a 105 mm Blank M365 artillery case in the clayey soil (Fig. 17b). The latter cartridge case is an artillery ammunition for 105 mm howitzers, used for salutes or simulating battlefield noise through the creation of sound, flash and smoke when ignited (GD-OTS, 2019). This artillery ammunition is formed by a shortened M14 case, which is filled with black powder, having at the base of the case, a M61 percussion element and a M1A2 primer.

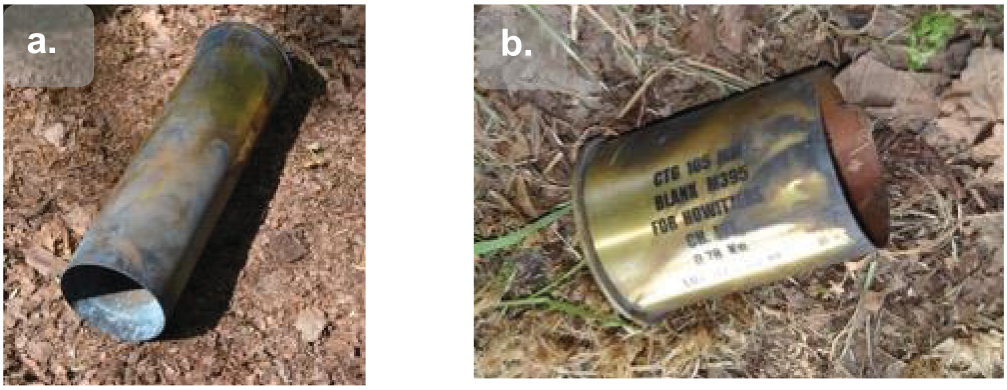

Figure 17. Artillery ammunition cases: a) 101 mm cartridge case and b) Blank M365 cartridge case.

The FIREND (Fig. 18) is a projectile designed for firefighting, a project proposed in 2005 (Lima, 2005) and upgraded in 2013 (Calado, 2013), changing from a 105 mm to a 155 mm projectile. In 2015, the projectile was again optimized, this time regarding the projectile material, from metallic to polymeric, allowing lower coast production, lower weight, and a reduction of environmental impact (Almeida, 2016). Thus, a FIREND is a polymeric artillery shell, aimed to assist firefighters and Civil Protection in fighting fires mainly in difficult access areas, reduced visibility and adverse weather conditions (Fonte-Boa *et al*., 2017). The FIREND was designed to be launched from a M114 Howitzer A1,155mm/23 (Almeida, 2016).

Figure 18. FIREND.

3.3. METHODOLOGY FOR DATA COLLECTION

3.3.1. PREPARATION OF THE STUDY SITES

First of all, each test site, with an area of 27 m^2 (3m x 9m), was delimited with wooden stakes and tape-measure, being posteriorly cleaned up in order to remove high vegetation. The cleanup was performed by a city hall worker that was already on site (Fig. 19).

Figure 19. Clayey soil study site clean-up.

3.3.2. CONTROL SCANNING

Previously to the explosive device's burial, it was performed a control scanning (Sc) on the two study sites with the 2D-Easyrad, using the antenna of 300 MHz (Fig. 20a). All scans were performed with the antenna elevated about 5-10 cm above the ground surface, which is advisable in shallow ground investigations for reduction of antenna-target and antenna-ground interactions (Chen *et al*., 2003). This survey was performed in order to have control datasets, to be able to futurly compare results and guarantee that the obtained signals in posterior GPR data are due to targets and not due to previously existing clutter (Hansen and Pringle, 2013).

In each study site, transects spaced by 0.2 m along the y direction were made, with the GPR being operated in parallel to the terrain's length (9 m). The beginning of each transect was marked with chalk (Fig. 20b), resulting in a total of 14 radargrams of each test site (Fig. 21). However, at the sandy soil, due to a concrete wall surrounding all study site, the initial and final position of both antennas, in each scan, was necessarly inside the study area, being the first acquisition point at 0.6 m (Fig. 6). Thus, the total study site length was about 7.8 m, beginning at 0.6 m and ending to 8.4 m, not being able to analise the total lengh (9 m). This restrain was not felt in the clayey soil study site, where each scan could beggin and end a little off the study area, allowing GPR to analise all 9 m.

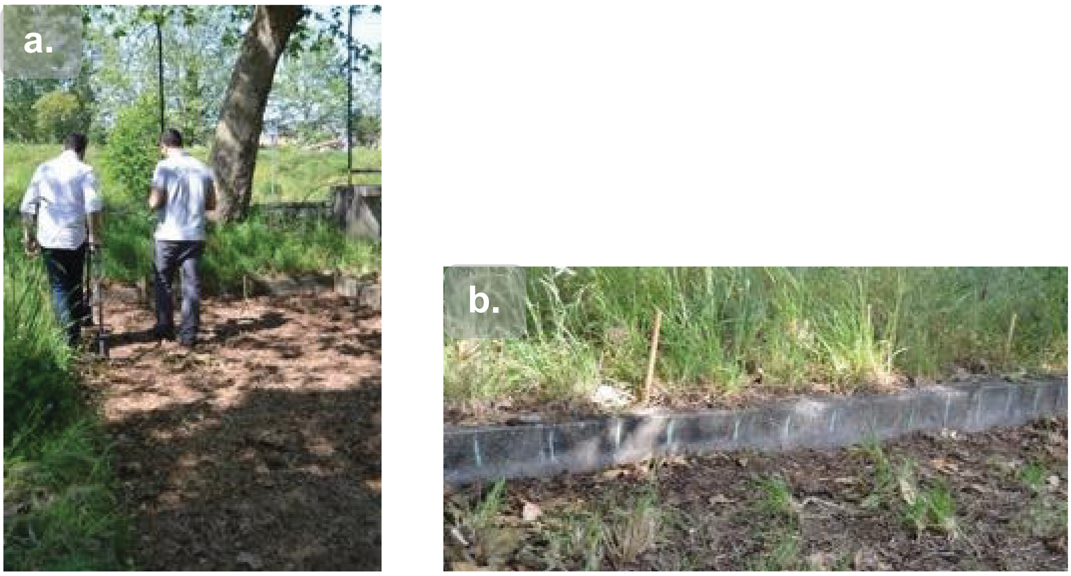

Figure 20. Control scanning: a) use of the 2D-Easyrad and the 300 MHz antennas; b) Chalk lines spaced by 0.2 m, marking the beginning of each survey line, along the 3 m side of the study site.

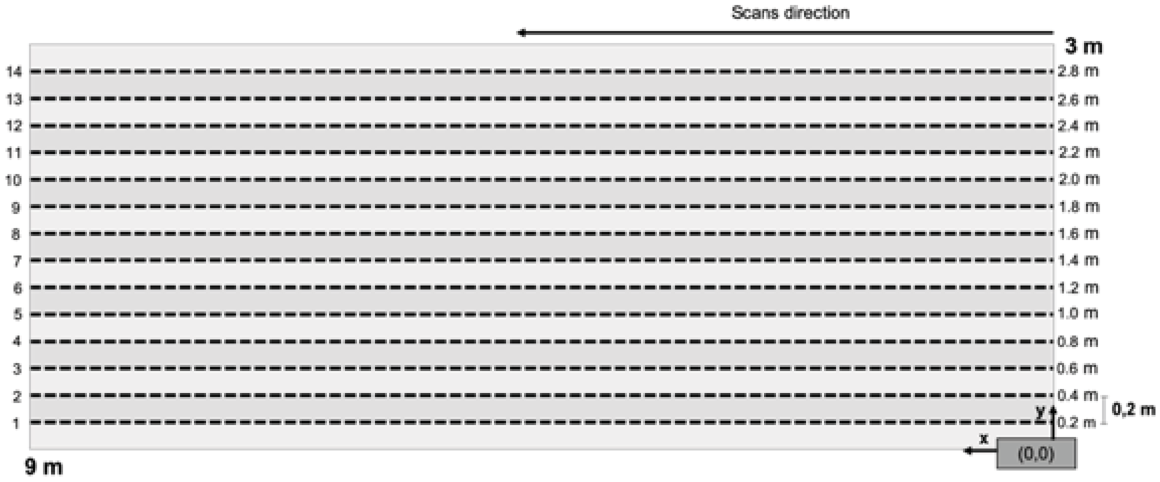

Figure 21. Schematic representation of the 14 parallel GPR scans performed on both study sites, with the 2D-Easyrad and 300 MHz frequency antenna (scans spaced by 0.2 metres along the y axis, beginning at 0.2 m (1st radargram) up to 2.8 m (14th radargram)).

3.3.3. TARGET’S BURIAL

After the performance of the Sc, a grid was established on each study site, using again the wooden stakes and tape-measure, dividing the study sites into 27 squares, each with an area of 1 m^2 (1m x 1m). Then, the position in which each target would be buried in the sandy (Fig. 22) and in the clayey soil type (Fig. 23) was decided. A total of 10 inert explosive devices, plus the negative an organic controls, were buried in the sandy soil and 11 inert explosive devices, plus the negative and organic controls, were also buried in the clayey soil type.

Inert explosive devices with different casing materials were used and different burial depths were practiced, in order to be able to posteriorly evaluate the capacity of GPR detection towards these variables. Thus, in the sandy soil study site 6 explosive devices had a metal casing, 3 had a plastic casing and 1 had a wooden casing; 2 were buried at 5 cm, 3 at 15 cm and 5 at 30 cm (Figs. 10a and 22; Table 3). In the clayey soil study site, 6 explosive devices had a metal casing, 4 had a plastic casing and 1 had a wooden casing; 2 were buried at 5 cm, 3 at 15 cm and 6 at 30 cm (Figs. 10b and 23; Table 3). The burial's depth for each target was chosen taking into account the normal depth at which they are encountered in real scenarios (Denefeld *et al*., 2017; Yip *et al*., 2015).

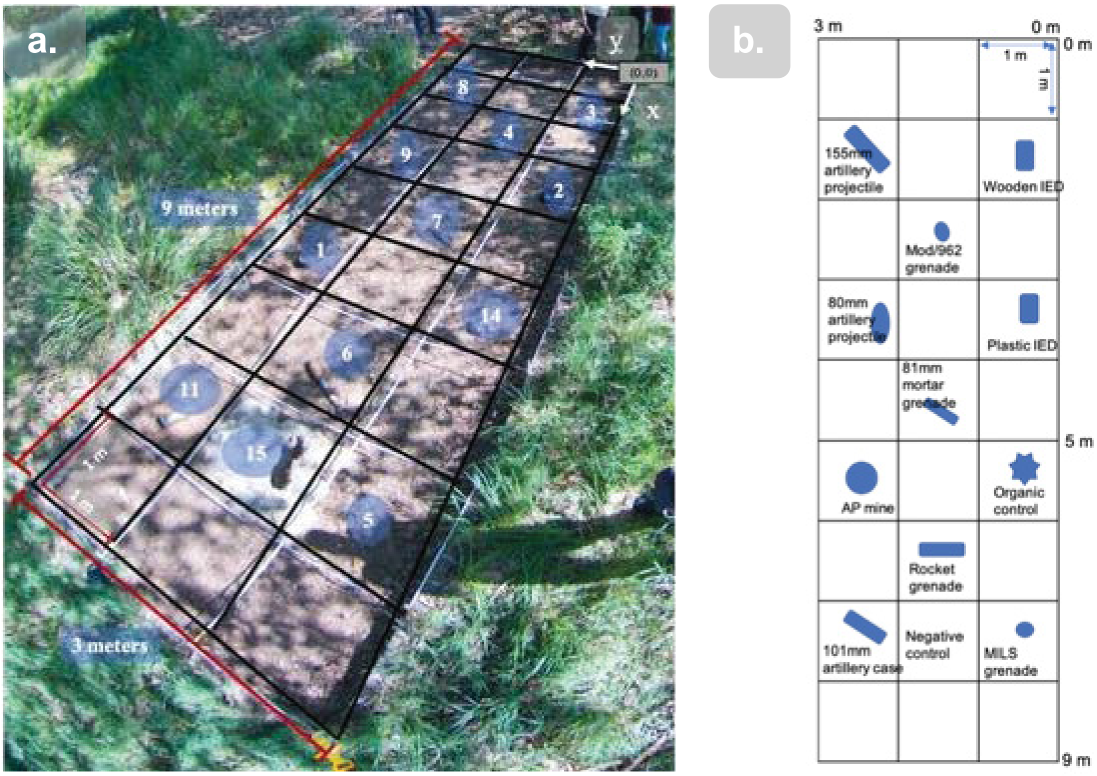

Figure 22. Sandy soil study site in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, Porto: a) aerial image with targets' distribution and b) schematic representation of targets' distribution.

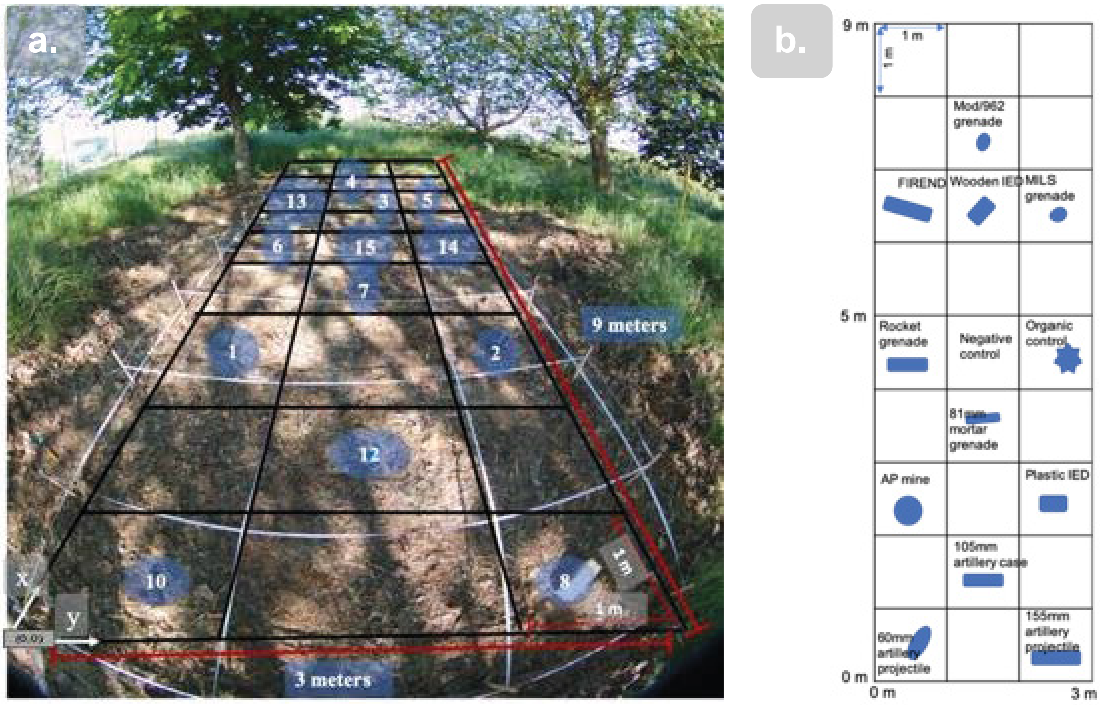

Figure 23. Clayey soil study site in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, Porto: a) aerial image with targets' distribution and b) schematic representation of targets' distribution.

Table 3. Targets buried in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, Porto (n/a= not applicable).

Nº	Buried targets	Casing Material	Depth (cm)	Nº	Buried targets	Casing Material	Depth (cm)
(1)	**Antipersonnel mine**	Plastic	15	(9)	**80 mm Artillery projectile**	Metal	30
(2)	**IED in a box**	Plastic	30	(10)	**60 mm Artillery projectile**	Metal	30
(3)	**IED in a box**	Wood	30	(11)	**101 mm Artillery case**	Metal	30
(4)	**Instruction hand grenade Mod/962**	Plastic	5	(12)	**105 mm Artillery case**	Metal	30
(5)	**MILLS hand grenade**	Metal	5	(13)	**FIREND**	Plastic	30
(6)	**Rocket grenade**	Metal	15	(14)	**Organic control**	n/a	30
(7)	**81 mm Mortar grenade**	Metal	15	(15)	**Negative control**	n/a	30
(8)	**155 mm Artillery projectile**	Metal	30				

During excavations, it was found that the box where the sandy soil was, also had cement at the bottom. Additionally, in the sandy soil study site, targets were not buried between 0-1 m and 8-9 m lenght (Fig. 22) due to the existent cement wall, forcing the beginning and ending of the scans inside the study site.

Also during excavations, it was also realized that the clayey soil study site was full of roots and anthropic material (*e.g.* glass and brick), which can be a further cause of clutter in GPR data. In this soil, between 5-6 metres lenght, there was a small cement beam, thus, targets were not buried there (Fig. 23).

3.3.4. GPR SURVEYS

After burying all the targets, GPR scans with the 300 MHz antenna were performed on each study site, corresponding to the zero survey (S0), aiming to compare results with the Sc and future surveys. Then, in each season of the year, other GPR surveys were performed.

The first seasonal survey (S1) was only performed two weeks after the target's burial, in order to let the natural compaction of the soil occur, being executed on May, in Spring (Hansen and Pringle, 2013). The burial action leads to the incorporation of air into the soil subsurface, which would cause erroneous readings if the S0 was considered the first survey, where most anomalies would be the result of air. In the S1, besides the 300 MHz antenna, it was also used the antenna of 100 MHz. Due to its bigger length, compared with the 300 MHz antenna, parallel line scans were spaced by 0.4 m along the y direction, resulting in a total of 6 radargrams for each soil type (Fig. 24). The 7th radargram, at 2.8 m could not be performed due to the concrete wall delimiting the sandy soil study site, leading to the inexistence of enough space for the antenna. By analogy, this last scan were also not performed at the clayey soil study site.

Aproximattly 3 months later, on September, the Summer survey (S2) was performed), using only the 300 MHz frequency antenna, due to better previous results.

The third survey (S3) was performed in November, in the Autumn season, using again both antennas, 300 MHz and 100 MHz, in order to be able to compare both in two intercalate seasons, with oposite environmental conditions (Spring and Autumn).

On March it was performed the Winter survey (S4), only using the 300 MHz antenna but also using a 3D-Radar. With the 3D-Radar system, due to its larger size, two parallel line scans, in each soil type, were enough to survey all study sites.

Previously to each GPR surveys, the test sites were manually cleanned up again, mainly in order to remove accumulated leaves on the soil.

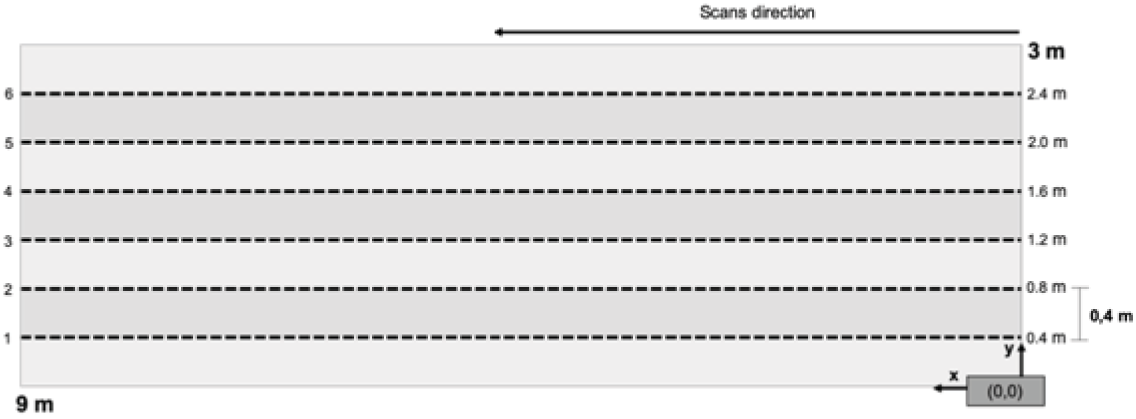

Figure 24. Schematic representation of the 6 parallel GPR scans performed on both study sites, with the 2D-Easyrad and 100 MHz frequency antenna (scans spaced by 0.4 metres along the y axis, beginning at 0.4 m (1st radargram) up to 2.4 m (6th radargram).

Table 4 summarizes all phases of the field study.

Table 4. Summary of all phases performed throughout the entire field work, with indication of the date, GPR system, used antennas, season of the year and the average temperature and total precipitation for each (source: AccuWeather), in the two weeks before the surveys (- = no data).

Phases	**Date**	**GPR**	**Antennas**	**Season**	**Average Temperature**	**Total Precipitation**
Preparation of the study sites	10/05/2018	-	-	-	-	-
Control Survey (Sc)	10/05/2018	2D-Easyrad	300 MHz	-	-	-
Target's burial	10/05/2018	-	-	-	-	-
Zero Survey (S0)	10/05/2018	2D-Easyrad	300 MHz	-	-	-
First Seasonal Survey (S1)	28/05/2018	2D-Easyrad	300 MHz 100 MHz	Spring	17.17 ºC	36 mm
Second Seasonal Survey (S2)	3/09/2018	2D-Easyrad	300 MHz	Summer	21.74 ºC	3 mm
Third Seasonal Survey (S3)	29/11/2018	2D-Easyrad	300 MHz 100 MHz	Autumn	13.6 ºC	173 mm
Fourth Seasonal Survey (S4)	22/03/2019	2D-Easyrad 3D-Radar	300 MHz -	Winter	12.3 ºC	8 mm

3.4.METHODOLOGY FOR DATA PROCESSING

GPR images/ results can suffer a lot of times from clutter, or background noise, originated by reflections from other sources besides the buried targets. These sources can be, for example, a small stone, a stratigraphic boundary, the reflection from the ground surface or the direct wave that is directly transmitted between transmitter and receiver antennas (Sato, 2009). If the signal from these secondary reflections is to strong, it can obscure the signal from the buried targets, making reduction of ground clutter the most important prerequisite for a consequent good GPR image interpretation. Thus, the processing techniques, applied to raw data, have the aim of enhancing the signal from the targets while diminishing the signals from clutter.

In the present work, the ReflexW software was used, being a program frequently used in academic and business issues, since it is designed specially to process GPR and Seismic data (Assunção, 2016; Gonçalves, 2013).

The raw data obtained with the 2D-Easyrad were imported as individual radargrams and the x and y value were defined. In the present study, the x value corresponded to the total length of each radargram (0 to 9 m for the clayey soil and 0.6 to 8.4 m for the sandy soil), and y value corresponded to the spacing between each parallel transect, being of 0.2 by 0.2 m for the 300 MHz frequency (from 0.2 to 2.8 m), and of 0.4 by 0.4 m for the 100 MHz frequency (from 0.4 to 2.4 m). The time window had to be also defined before processing, being of 75 ns, and the velocity of the EM waves, correctly measured, were defined at 0.11 m/ ns, to transform the time scale into depth scale, resulting in a radargram with a total depth of approximately 4 m (Fig. 25). Then, each individual radargram were processed using the following methodology (Annan *et al.*, 1991; Daniels, 2000):

1. Low frequency clutter filter removal (Dewow);
2. Background noise filter removal (Background Removal);
3. Bandpass Butterworth;
4. Running average.

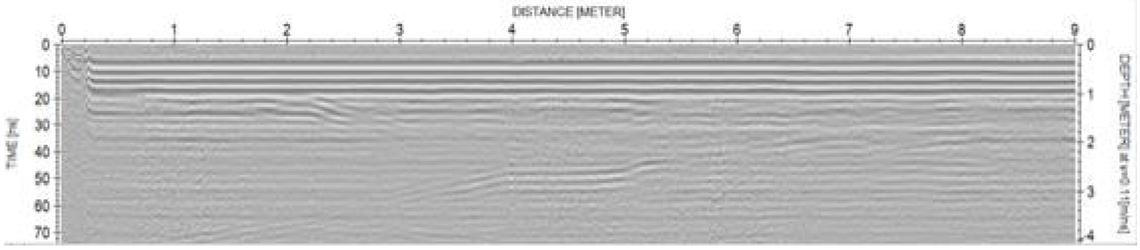

Figure 25. Radargram 1 of the S0 made at the clayey soil study site, without processing.

The first filter applied was the subtract-mean, or Dewow, with the intention of removing the very low frequencies. This results in an image with a more equilibrated colour scale (Fig. 26).

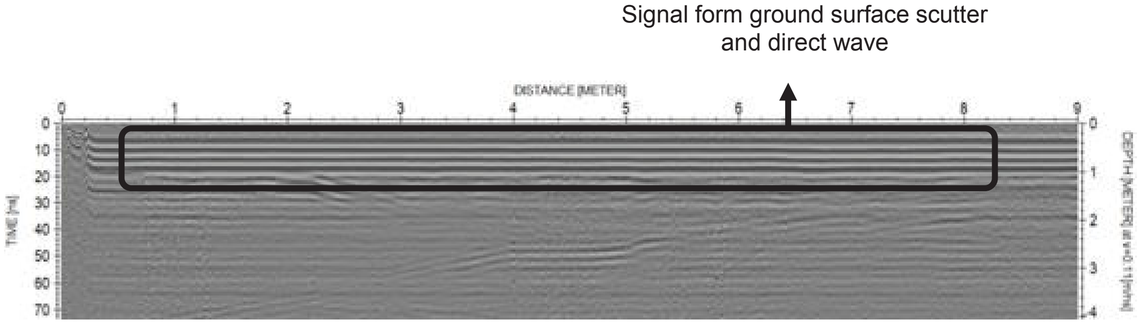

Figure 26. Radargram 1 of the S0 made at the clayey soil study site, with application of the Subtract-mean filter (Dewow).

Posteriorly, it was applied the background removal, a 2D-filter, to all window time travel, contributing to the enhancement of subsoil signals through the removal of the first and stronger signals received by the GPR antenna (Fig. 26), caused by ground surface scutter due to the interface air/ soil, and direct wave transmitted between antennas (Fig. 27).

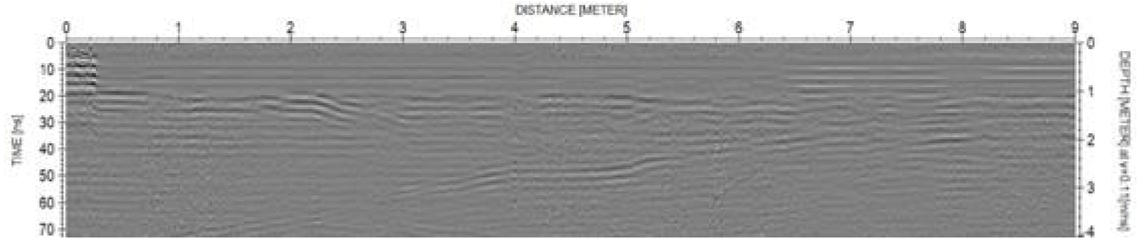

Figure 27. Radargram 1 of the S0 made at the clayey soil study site, with application of the Background Removal filter.

Next filter applied was the bandpass butterworth, a 1D-filter, which means that it is only applied trace by trace, operating between frequencies, removing, in this case, any frequency below 30 MHz or above 400 MHz. The result is a clearer image, with signals from potential buried targets enhanced (Fig. 28).

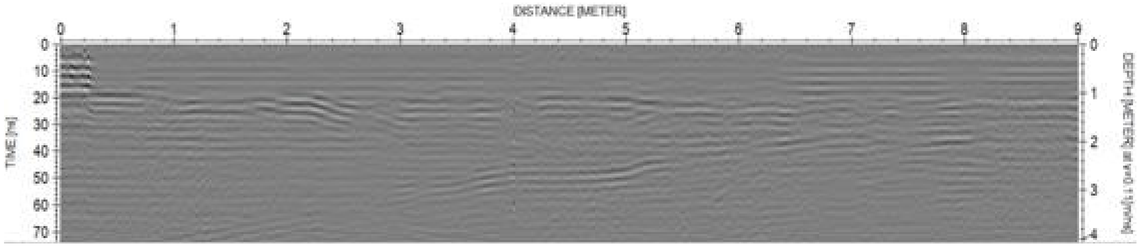

Figure 28. Radargram 1 of the S0 made at the clayey soil study site, after application of the Bandpass Butterworth filter of 30 MHz and 400 MHz.

The final step of this processing methodology was the application of running average, a 2D-filter that performs the average every two traces. The result is an image with better resolution with stronger enhancement of signals from subsurface targets (Fig. 29).

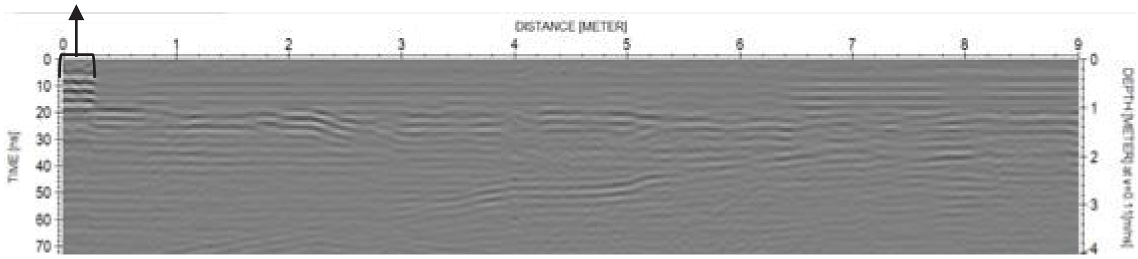
Reflections due to an immobile GPR recording

Figure 29. Radargram 1 of the S0 made at the clayey soil study site, after application of the Running Average filter.

Before starting the scans, the 2D GPR can stays immobile during a short period of time while recording, obtaining characteristic signals that can be observed in the radargrams (Fig. 29). Thus, after processing, it is also necessary to correct the zero time manually for each radargram (Fig. 30). For this, it was used the “edit traces/ trace ranges” command to eliminate these unwanted signals. Then, the total length of the radargrams must be changed to the correct length (in this case 0-9 m; Fig. 31), using the command “Edit file header of the actual line”.

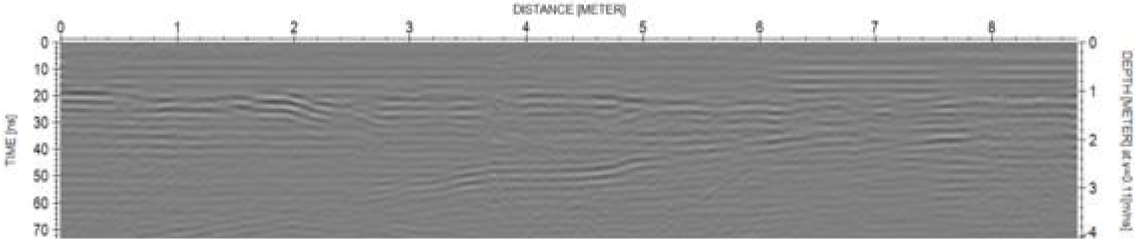

Figure 30. Radargram 1 of the S0 made at the clayey soil study site, after zero-time correction.

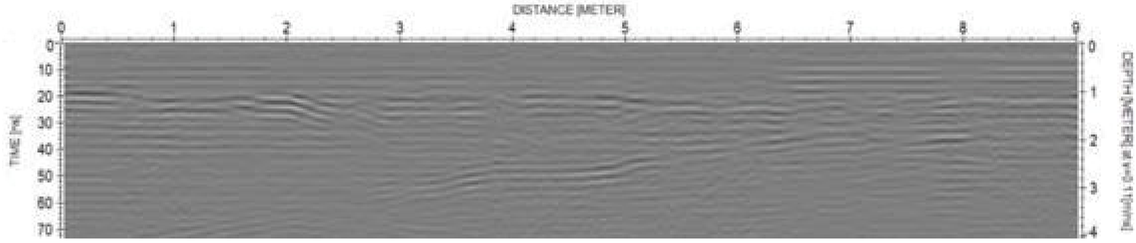

Figure 31. Radargram 1 of the S0 made at the clayey soil study site, after correction of the total profile length (0-9 m).

Data obtained with the 3D-Radar were also imported to the ReflexW software as individual radargrams, with the same specifications of x, y and time window values. The following processing steps were applied:

1. Subtract-mean (Dewow) on the 50 ns of every section;
2. Background Removal;
3. Bandpass Butterworth between 500 and 1800 MHz;
4. Divergence compensation;
5. Energy decay.

The processed radargrams were then used to create 3D-cubes with the ReflexW 3D software, by interpolation between the consecutive parallel 2D profiles previously processed. As it was used pre-processed 2D data, the only additional process technique that was applied was migration (Kirchhoff). Migration is used to trace back the reflection and diffraction energy to their “source” (Tellez and Scheers, 2017), which will give us a better approximation to the real target depth.

3.5. METHODOLOGY FOR DATA PRESENTATION

Results are presented in two different formats: 2D-radargrams, where it is represented the total length of the study area in function of the travel time (ns)/ depth(m) for individual horizontal line scans; and 3D-cubes, which are representations of the whole scanned study sites, with parallel 2D-radargrams compiled in one single image.

GPR signals that could be correlated with target positions (Figs. 22 and 23) are searched and identified in the radargrams (2D-Easyrad data) and 3D-cubes (3D-Radar data). The total percentage of explosive devices (EDs) detection were calculated at each season survey, for each GPR and used antenna. Furthermore, it was also calculated the percentage of detection towards the type of casing material and burial depth, taking into account the total number of representative buried EDs.

Due to the large quantity of GPR data only some radargrams, with interesting target's reflected signals, are presented.

IV. RESULTS

4.1. CONTROL SURVEY (SC) AND ZERO SURVEY (S0)

For these two surveys, only 3D-cubes obtained from parallel radargrams were analysed, since the aim was not knowing which targets were detected, but if the interferences were enhanced after target's burial, being the view of the whole study sites more useful. Time slices at a depth of approximately 1.5 m are presented, being where the signals from the buried targets were detected.

4.1.1. SANDY SOIL STUDY SITE

Comparing the 3D-cubes taking at the sandy soil study site with the 300 MHz antenna in the Sc (Fig. 32) and S0 (Fig. 33), it was clearly observed that the soil was perturbed due to the burial of the targets, an action that results also in the incorporation of air in the subsoil. Even in places where no targets were buried the ground penetrating radar (GPR) detected some perturbations on the subsoil (between 0-1 m of the x axis; Fig. 33), meaning that the action of bury an object will probably affect not only the burial place, but also the surrounding soil.

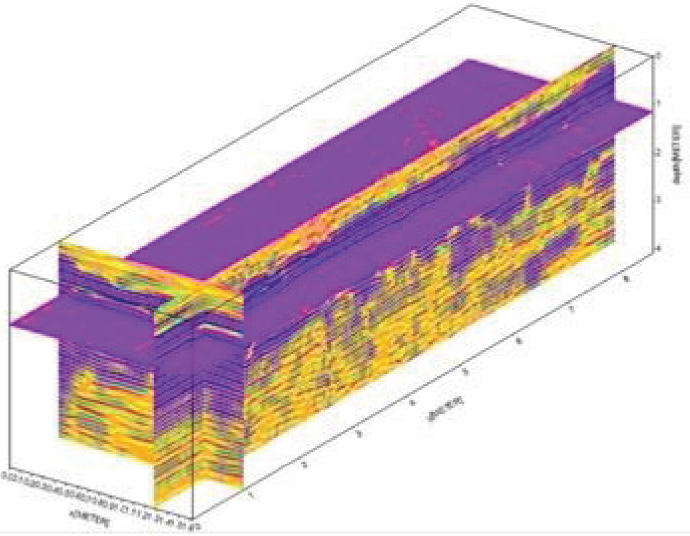

Figure 32. 3D geophysical model of the control survey (Sc) in the sandy soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, performed with the 300 MHz frequency antenna of the 2D-Easyrad georadar.

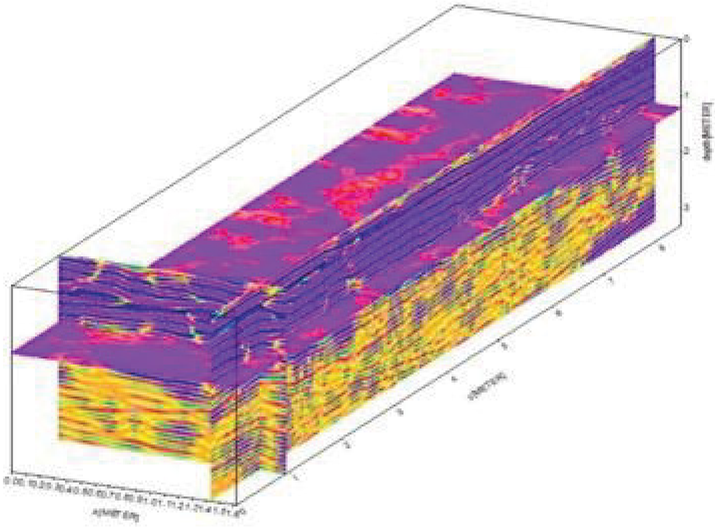

Figure 33. 3D geophysical model of the zero survey (S0) in the sandy soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, performed with the 300 MHz frequency antenna of the 2D-Easyrad georadar.

4.1.2.CLAYEY SOIL STUDY SITE

In the clayey soil study site, comparing with the sandy soil (Fig. 32), more perturbations were observed on the subsurface in the Sc (Fig. 34). This is probably due to the heterogeneity of the clayey soil study site, with the presence of objects of anthropic origin, like plastic, tiles, glass, and also the presence of many roots. Like the previous results for the sandy soil, it is clearly noticeable the enhancement of subsoil perturbations as a result of targets burial in the S0 (Fig. 35).

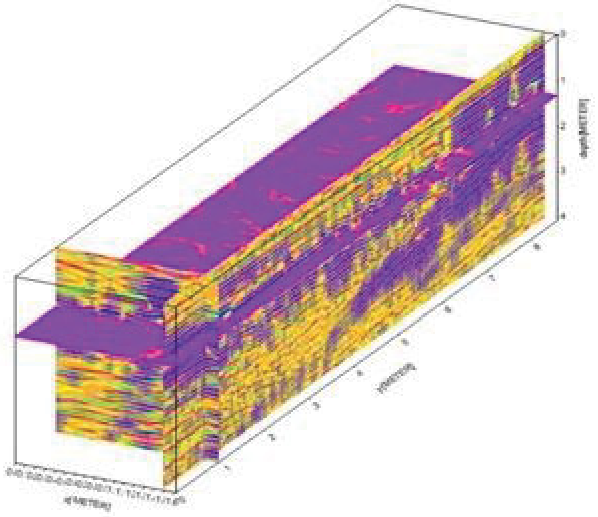

Figure 34. 3D geophysical model of the control survey (Sc) in the clayey soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, performed with the 300 MHz frequency antenna of the 2D-Easyrad georadar.

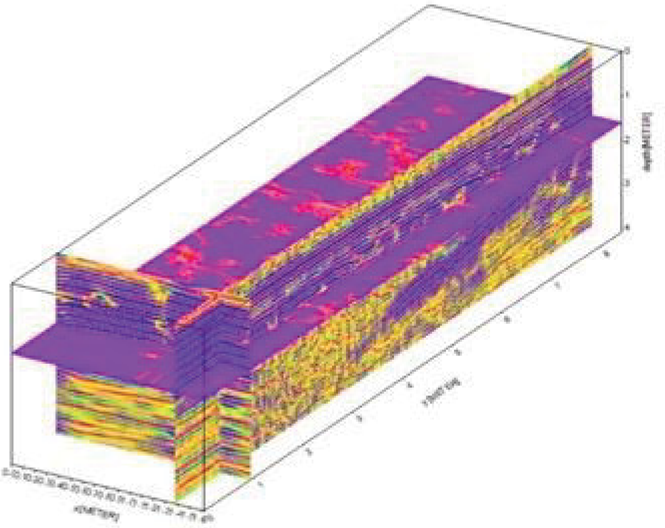

Figure 35. 3D geophysical model of the zero survey (S0) in the clayey soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, performed with the 300 MHz frequency antenna of the 2D-Easyrad georadar.

4.2. SPRING SURVEY (S1)

In the S1, performed in the Spring season, the 300 MHz and 100 MHz frequency antennas were both used in each study site. GPR profiles for the 300 MHz frequency antenna were obtained 0.2 in 0.2 metres, along the y axis of the two study sites, resulting in 14 radargrams (Fig. 21). The profiles with the 100 MHz frequency antenna were obtained 0.4 in 0.4 metres, along the same side, resulting in 6 radargrams (Fig. 24). As this survey was performed two weeks after the S0 with the intention of obtaining soil compaction, 3D-cubes are also presented so this effect could be better observed.

4.2.1. SANDY SOIL STUDY SITE

Analysing each individual radargram obtained with the 300 MHz frequency antenna, it was identified some hyperbolic shape signals that could be correlated with the burial positions (Fig. 22; Table 3) of: MILLS hand grenade (5), rocket grenade (6), 81 mm mortar grenade (7; Fig. 36), 155 mm artillery projectile (8), 80 mm artillery projectile (9), 101 mm artillery case (11), organic control (14) and negative control (15). Thus, 6 EDs were detected corresponding to a percentage of detection of 60.00%, being 6 metal EDs (100.00%); 1 buried at 5 cm (50.00%), 2 at 15 cm (66.67%) and 3 at 30 cm (60.00%; Tables 5 and 7).

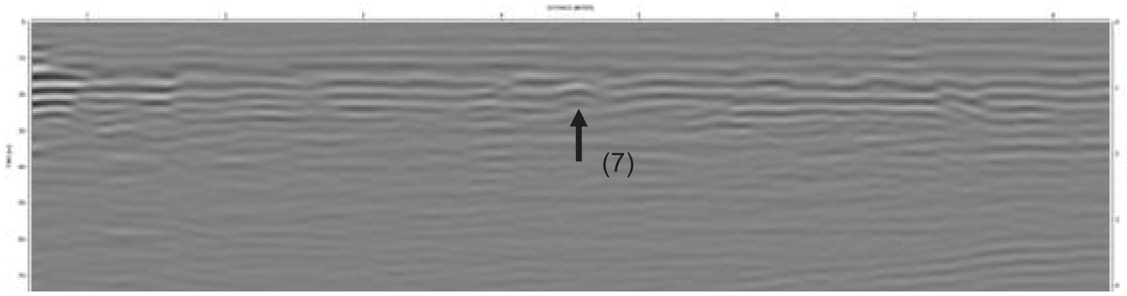

Figure 36. Spring season (S1) radargram at 1.2 m of the y axis of the sandy soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, using the 300 MHz antenna of the 2D-Easyrad georadar, with indication of the signal correspondent to the burial position of the 81 mm mortar grenade (7) buried between 4 and 5 m of the x axis.

With the 100 MHz antenna, although the lower resolution, it was possible to detect signals that could be correlated with burial positions (Fig. 22; Table 3) of: instruction hand grenade Mod/962 (4), 81 mm mortar grenade (7), 101 mm artillery case (11) and organic control (14; Fig. 37). A total of 3 EDs were detected, corresponding to a percentage of detection of 30.00%, being 2 metal EDs (33.33%) and 1 plastic ED (33.33%); 1 buried at 5 cm (50.00%), 1 at 15 cm (33.33%) and 1 at 30 cm (20.00%; Tables 5 and 7).

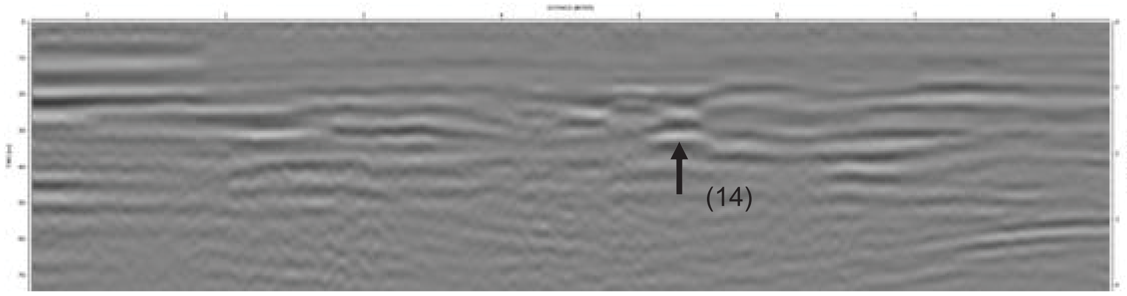

Figure 37. Spring season (S1) radargram at 0.4 m of the y axis of the sandy soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, using the 100 MHz antenna of the 2D-Easyrad georadar with indication of the signal correspondent to the burial position of the organic control (14) buried between 5 and 6 m of the x axis.

Comparing the 3D-cube from the S0 (Fig. 33) with the 3D-cube from the S1 (Fig. 38), it was observe that, although low, some soil compaction occurred, being eliminated signal interferences that may come from air on the ground, due to the burial process. It is still observed some false positives, which means that interferences in places where no object was buried were seen.

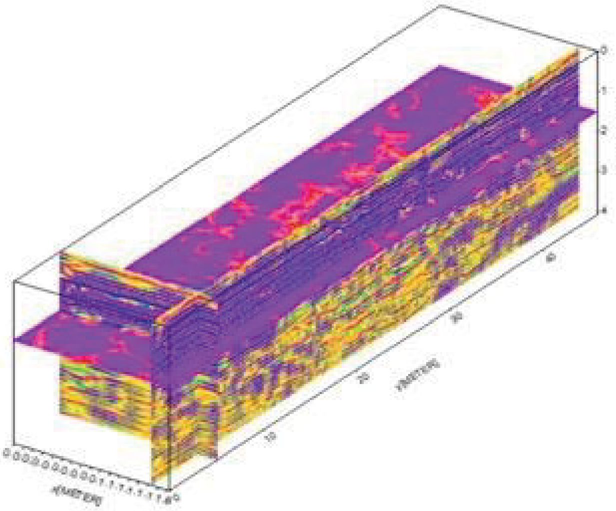

Figure 38. 3D geophysical model of the Spring survey (S1) in the sandy soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, performed with the 300 MHz frequency antenna of the 2D-Easyrad georadar.

4.2.2. CLAYEY SOIL STUDY SITE

With the 300 MHz antenna, some hyperbolic shape signals could be correlated with the burial positions (Fig. 23; Table 3) of: antipersonnel (AP) mine (1), improvised explosive device (IED) in a wooden box (3), rocket grenade (6; Fig. 39), 155 mm artillery projectile (8), 60 mm artillery projectile (10), 105 mm artillery case (12), and firend (13; Fig. 39). A total of 7 EDs were detected, which corresponds to a percentage of detection of 64.00%, being 4 metal EDs (66.67%), 2 plastic EDs (50.00%), 1 wooden ED (100.00%); 2 buried at 15 cm (66.67%) and 5 buried at 30 cm (83.33%; Tables 5 and 7).

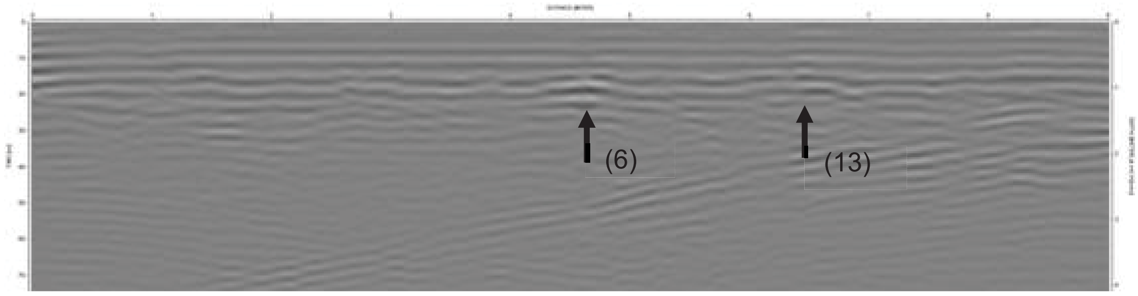

Figure 39. Spring season (S1) radargram at 0.2 m of the y axis of the clayey soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, using the 300 MHz antenna of the 2D-Easyrad georadar, with indication of the signals correspondent to the burial positions of the rocket grenade (6) buried between 4 and 5 m of the x axis, and the firend (13) buried between 6 and 7 m of the x axis.

With the 100 MHz antenna, the only detected target was the 105 mm artillery case (12; Fig. 40), corresponding to a percentage of detection of 9.00%, being a metal ED (17.00%) buried at 30 cm (17.00%; Tables 5 and 7).

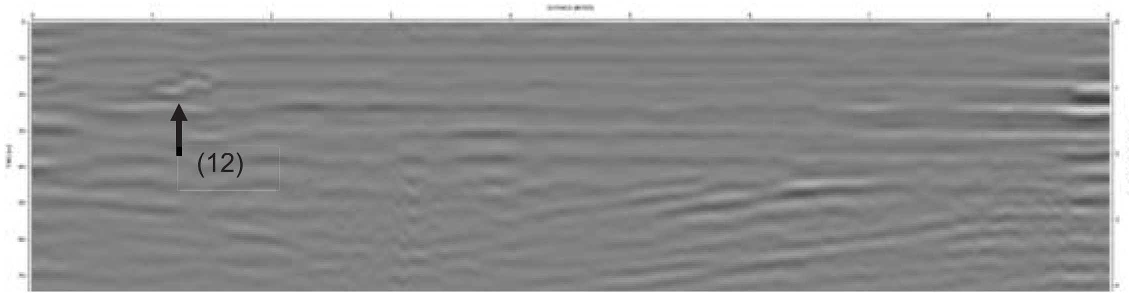

Figure 40. Spring season (S1) radargram at 1.2 m of the y axis of the clayey soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, using the 100 MHz antenna of the 2D-Easyrad georadar, with indication of the signal correspondent to the burial position of the 105 mm artillery case (12) buried between 1 and 2 m of the x axis.

It is also important to notice that in all clayey soil radargrams, especially the first ones taken with the 300 MHz frequency antenna, it was clearly observed an interference possibly from the cement beam (Fig. 41) present in the study site.

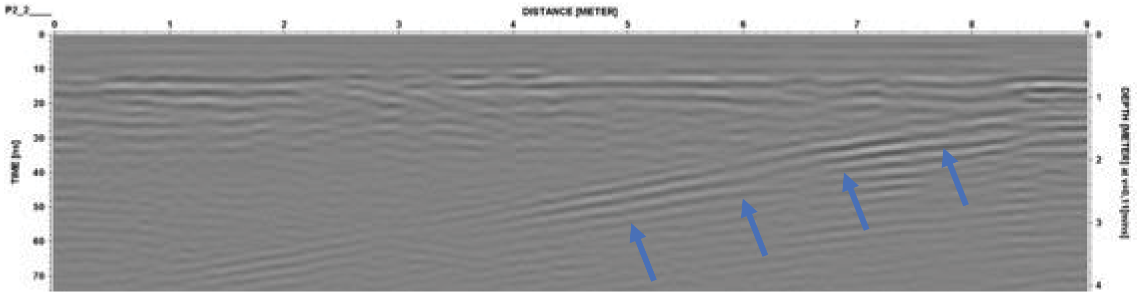

Figure 41. Spring season (S1) radargram at 0.4 m of the y axis of the clayey soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, using the 300 MHz antenna of the 2D-Easyrad georadar, with identification of a continuous interference signal possibly from the concrete beam that surrounded the test site.

Comparing the 3D-cube from the S0 (Fig. 35) with the 3D-cube from the S1 (Fig. 42), it was observed signal enhancement in some regions of the time slice, probably due to low compaction and effective detection of those specific targets, being also observed a signal decrease in other regions, possibly due to the soil compaction in those specific areas.

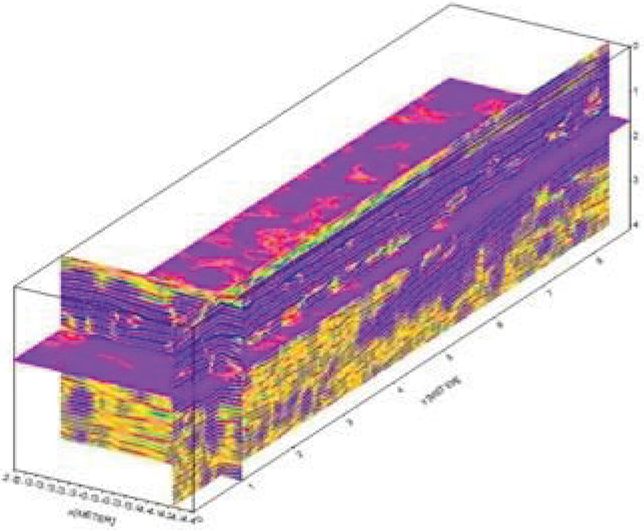

Figure 42. 3D geophysical model of the Spring survey (S1) in the clayey soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, performed with the 300 MHz frequency antenna of the 2D-Easyrad georadar.

4.3. SUMMER SURVEY (S2)

In this season, only the 300 MHz frequency antenna was used due to better previous results, resulting in a total of 14 radargrams for each study site.

4.3.1. SANDY SOIL STUDY SITE

Observing all processed radargrams, some hyperbolic shape signals were identified that could be correlated with the burial positions (Fig. 22; Table 3) of: IED in a wooden box (3), MILLS hand grenade (5), rocket grenade (6; Fig. 43), 81 mm mortar grenade (7; Fig. 43), 155 mm artillery projectile (8; Fig. 44), 101 mm artillery case (11; Fig. 44), organic control (14) and negative control (15; Fig. 43). A total of 6 EDs were detected, corresponding to a percentage of detection of 60.00%, being 5 with metal casing (83.33%) and the only wood ED (100.00%); 1 buried at 5 cm (50.00%), 2 at 15 cm (66.67%) and 3 at 30 cm (60.00%; Tables 5 and 7).

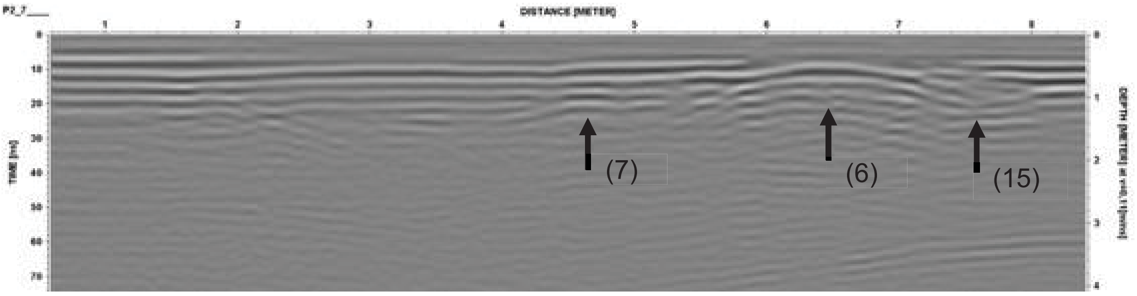

Figure 43. Summer season (S2) radargram at 1.4 m of the y axis of the sandy soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, using the 300 MHz antenna of the 2D-Easyrad georadar, with indication of the signals correspondent to the burial positions of the 81 mm mortar grenade (7) buried between 4 and 5 m of the x axis, the rocket grenade (6) buried between 6 and 7 m of the x axis, and the negative control (15) buried between 7 and 8 m of the x axis.

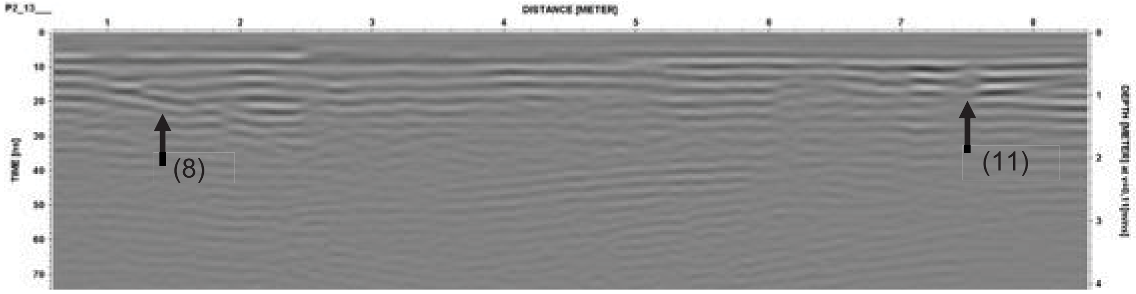

Figure 44. Summer season (S2) radargram at 2.6 m of the y axis of the sandy soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, using the 300 MHz antenna of the 2D-Easyrad georadar, with indication of signals correspondent to the burial positions of the 155 mm artillery projectile (8) buried between 1 and 2 m of the x axis, and the 101 mm artillery case (11) buried between 7 and 8 m of the x axis.

4.3.2. CLAYEY SOIL STUDY SITE

In the radargrams it was identified some hyperbolic shape signals that could be correlated with the burial positions (Fig. 23; Table 3) of: AP mine (1; Fig. 45), instruction hand grenade Mod/962 (4), rocket grenade (6), 81 mm mortar grenade (7), 60 mm artillery projectile (10; Fig. 45), 105 mm artillery case (12) and firend (13). The total number of detected targets was 7, corresponding to a percentage of detection of 64.00%, being 4 metal EDs (66.67%) and 3 plastic EDs (75.00%); 1 buried at 5 cm (50.00%), 3 at 15 cm (100.00%) and 3 at 30 cm (50.00%; Tables 5 and 7).

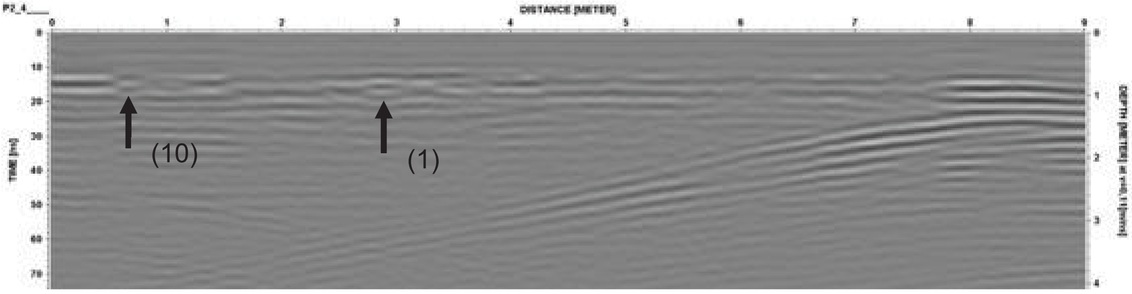

Figure 45. Summer season (S2) radargram at 0.8 m of the y axis of the clayey soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, using the 300 MHz antenna of the 2D-Easyrad georadar, with indication of the signals correspondent to the burial positions of 60 mm artillery shell (10) buried between 0 and 1 m of the x axis, and the AP mine (1) buried between 2 and 3 m of the x axis.

4.4. AUTUMN SURVEY (S3)

In the S3, scans were performed with the two 2D-Easyrad antennas, 300 MHz and 100 MHz, as in the S1, in order to be able to have a comparison between two seasons with opposite environmental conditions. Like in previous surveys, a total of 14 radargrams where obtained with the 300 MHz frequency antenna, being obtained 6 radargrams with the 100 MHz frequency antenna, for each study site.

4.4.1. SANDY SOIL STUDY SITE

With the 300 MHz antenna it was possible to identify in the radargrams some hyperbolic shape signals that could be correlated with the burial positions (Fig. 22; Table 3) of: MILLS hand grenade (5; Fig. 46), rocket grenade (6; Fig. 47) and organic control (14; Fig. 46). A total of 2 EDs were detected, which correspond to a percentage of detection of 20.00%, being 2 metal EDs (33.33%); 1 buried at 5 cm (50.00%) and 1 buried at 15 cm (33.33%; Tables 5 and 7).

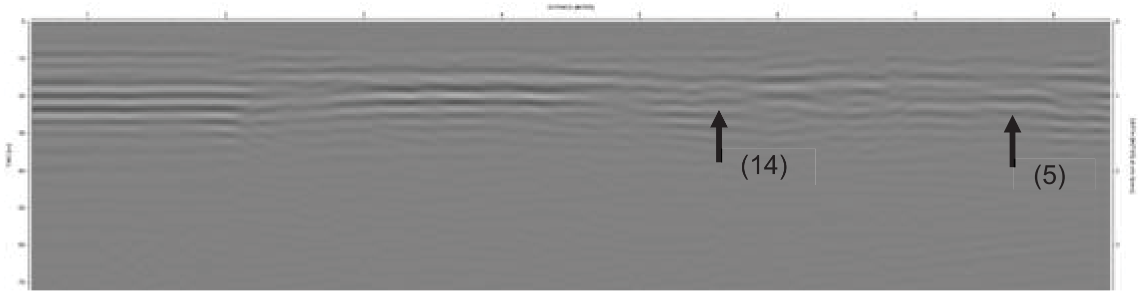

Figure 46. Autumn season (S3) radargram at 0.6 m of the y axis of the sandy soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, using the 300 MHz antenna of the 2D-Easyrad georadar, with indication of the signals correspondent to the burial positions of the organic control (14) buried between 5 and 6 m of the x axis, and the MILLS hand grenade (5) buried between 7 and 8 m of the x axis.

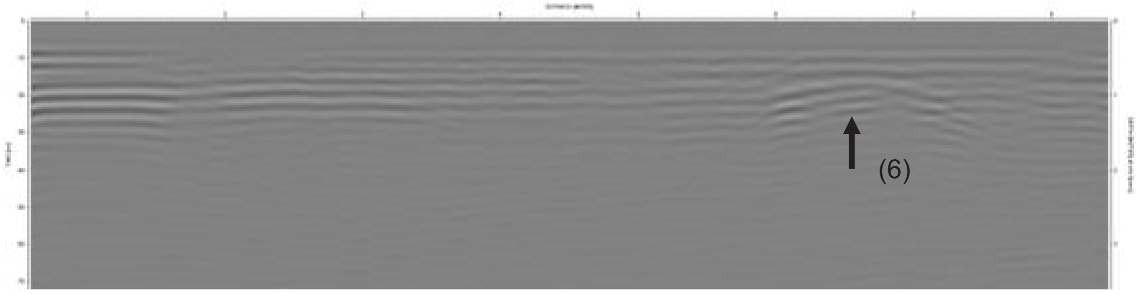

Figure 47. Autumn season (S3) radargram at 1.8 m of the y axis of the sandy soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, using the 300 MHz antenna of the 2D-Easyrad georadar, with indication of the signal correspondent to the burial position of the rocket grenade (6) buried between 6 and 7 m of the x axis.

With the 100 MHz antenna, only one target was possibly detected, the 81 mm mortar grenade (7; Fig. 48), corresponding to a percentage of detection of 10.00%, being a metal ED (17.00%) buried at 15 cm (33.33%; Tables 5 and 7).

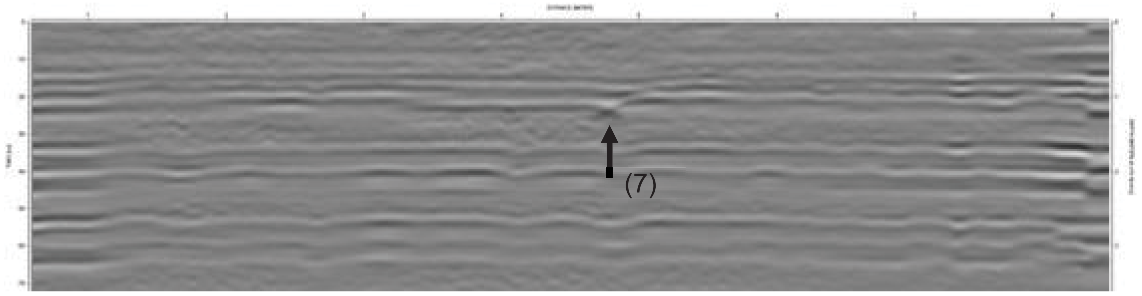

Figure 48. Autumn season (S3) radargram at 1.6 m of the y axis of the sandy soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, using the 100 MHz antenna of the 2D-Easyrad georadar, with indication of the signal correspondent to the burial position of the 81 mm mortar grenade (7) buried between 4 and 5 m of the x axis.

4.4.2. CLAYEY SOIL STUDY SITE

With the 300 MHz frequency antenna, it was possible to identify some hyperbolic shape signals that could be correlated with the burial positions (Fig. 23; Table 3) of: AP mine (1; Fig. 49), rocket grenade (6; Fig. 49), 81 mm mortar grenade (7), 105 mm artillery case (12) and firend (13; Fig. 49). A total of 5 EDs were detected, which corresponds to a percentage of detection of 45.00%, being 3 metal EDs (50.00%) and 2 plastic EDs (50.00%); 3 buried at 15 cm (100.00%) and 2 at 30 cm (33.33%; Tables 5 and 7).

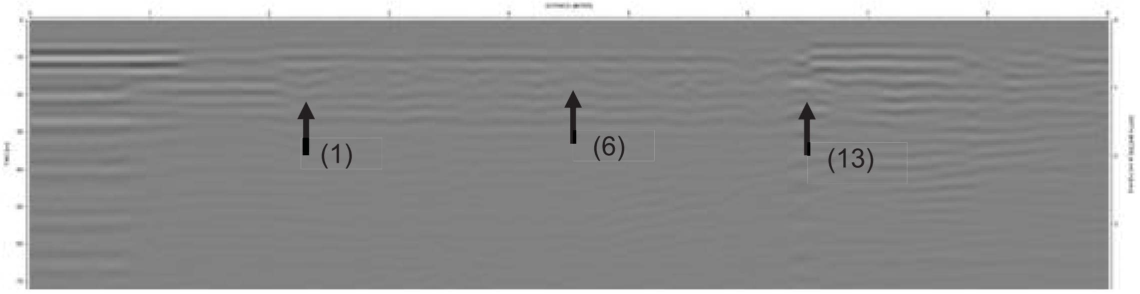

Figure 49. Autumn season (S3) radargram at 0.6 m of the y axis of the clayey soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, using the 300 MHz antenna of the 2D-Easyrad georadar, with indication of the signals correspondent to the burial positions of the AP mine (1) buried between 2 and 3 m of the x axis, the rocket grenade (6) buried between 4 and 5 m of the x axis, and the firend (13) buried between 6 and 7 m of the x axis.

With the 100 MHz frequency antenna no target was detected (Tables 5 and 7).

4.5. WINTER SURVEY (S4)

In the S4, besides the use of the 2D-Easyrad with the 300 MHz frequency antenna, resulting in 14 radargrams for each study site, the ground surface was also scanned with the 3D-Radar.

4.5.1.SANDY SOIL STUDY SITE

Observing the radargrams, some hyperbolic shape signals could be correlated with the burial positions (Fig. 22; Table 3) of: IED in a plastic box (2), IED in a wooden box (3), rocket grenade (6; Fig. 50), 81 mm mortar grenade (7), 80 mm artillery projectile (9) and organic control (14). A total of 5 EDs were detected, corresponding to a percentage of detection of 50.00%, being 3 metal EDs (50.00%), 1 plastic ED (33.33%) and 1 wooden ED (100.00%); 2 buried at 15 cm (66.67%) and 3 at 30 cm (60.00%; Tables 5 and 7).

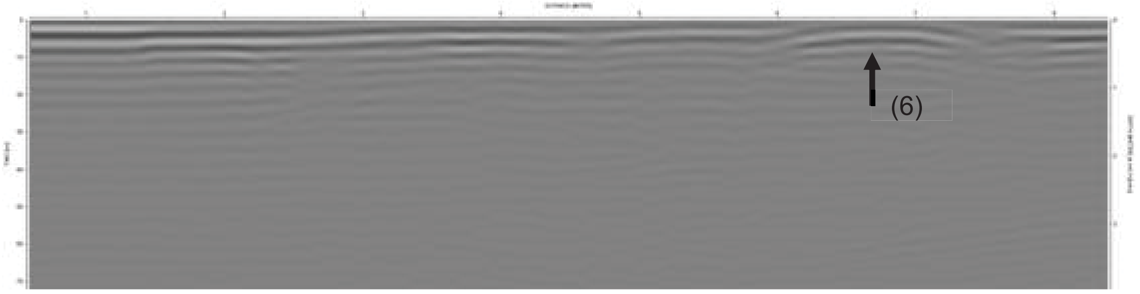

Figure 50. Winter season (S4) radargram at 1.2 m of the y axis of the sandy soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, using the 300 MHz antenna of the 2D-Easyrad georadar, with indication of the signal correspondent to the burial position of the rocket grenade (6) buried between 6 and 7 m of the x axis.

With the 3D-Radar, all buried targets were detected, regardless the considered variables (Fig. 51; Table 5).

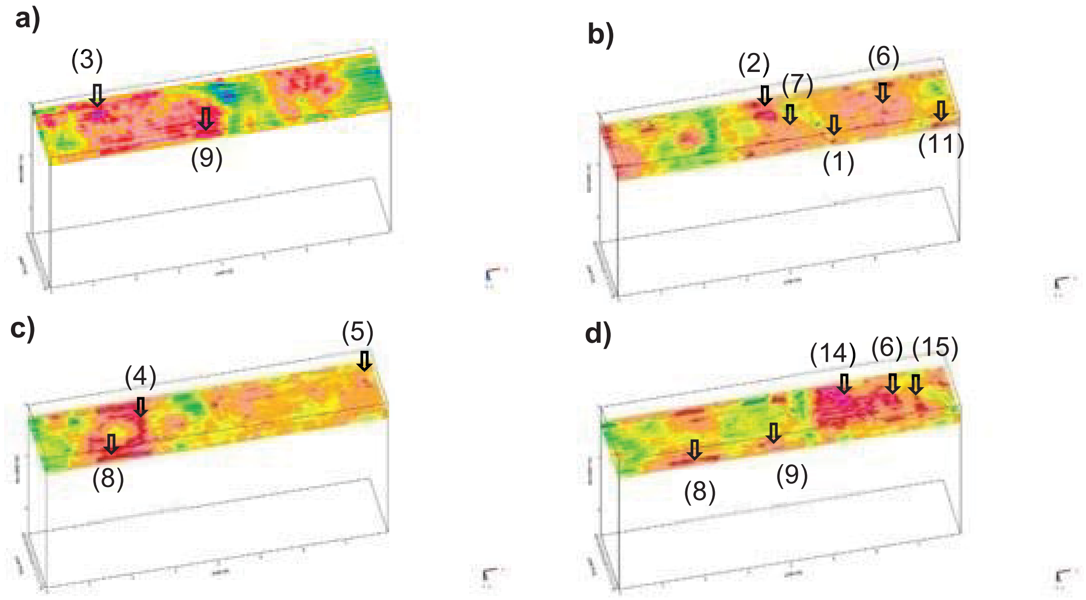

Figure 51. Four time slices of a 3D geophysical model, between 5-10 cm up to 30-40 cm in depth, of the sandy soil study site, located in the facility of the Military Unit of Serra do Pilar, Vila Nova de Gaia. In each time slice, arrows indicate regions where signals could be correlated with target's positions.

4.5.2.CLAYEY SOIL STUDY SITE

Some identified hyperbolic shape signals at the radargrams could be correlated with the burial positions (Fig. 23; Table 3) of: AP mine (1), IED in a wooden box (3; Fig. 52), MILLS hand grenade (5), rocket grenade (6), 81 mm mortar grenade (7; Fig. 52) and firend (13). A total of 6 explosive devices were detected, resulting in a percentage of detection of 54.00%, being 3 metal EDs (50.00%), 2 plastic EDs (50.00%) and 1 wooden ED (100.00%); 1 buried at 5 cm (50.00%), 3 at 15 cm (100.00%) and 2 at 30 cm (33.33%; Tables 5 and 7).

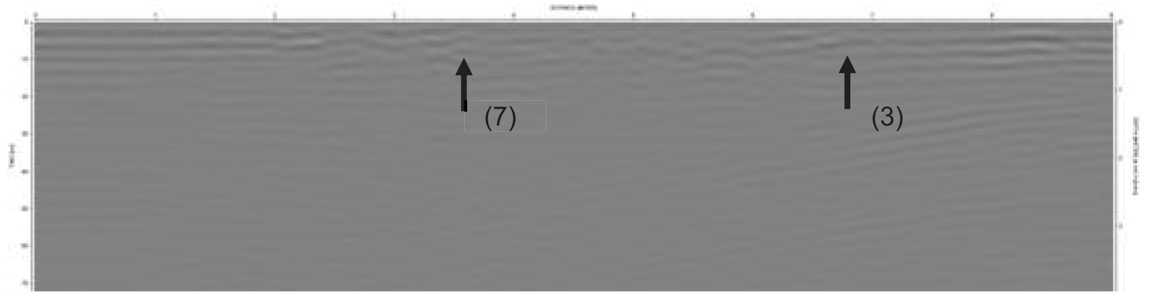

Figure 52. Winter season (S4) radargram at 1.8 m of the y axis of the clayey soil study site, located in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, using the 300 MHz antenna of the 2D-Easyrad georadar, with indication of signals correspondent to the burial positions of 81 mm mortar grenade (7) buried between 3 and 4 m of the x axis, and the IED in a wooden box (3) buried between 6 and 7 m of the x axis.

As in the sandy soil study site, with the 3D-Radar all buried inert EDs and the two controls were detected, regardless the considered variables (Fig. 53; Table 5).

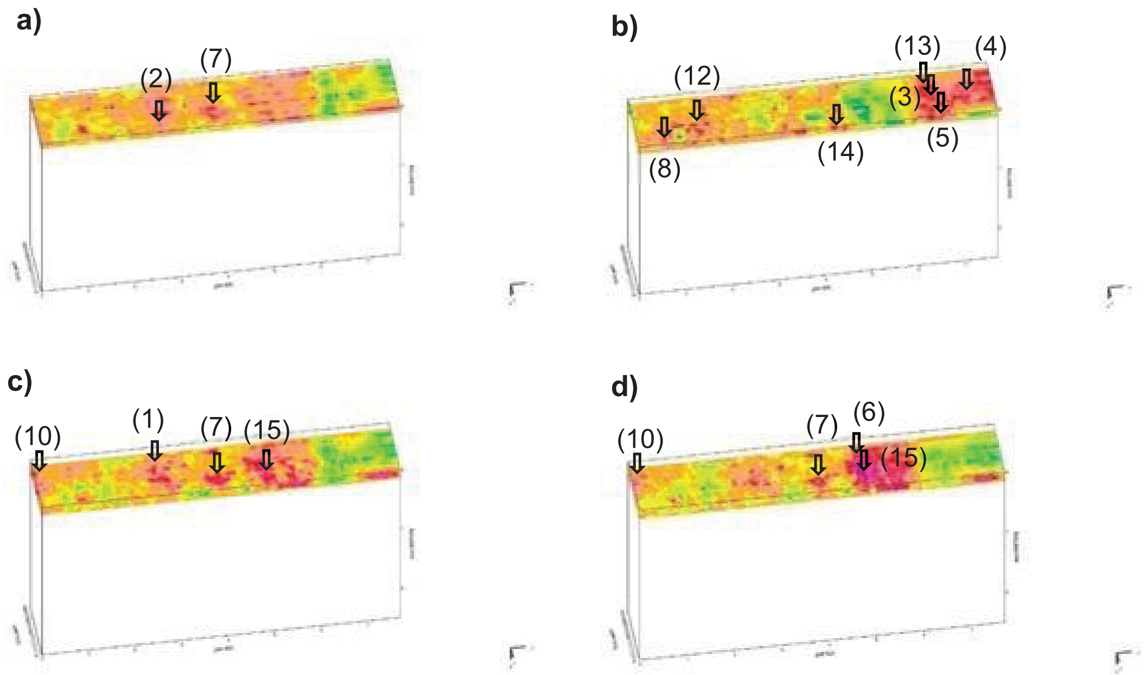

Figure 53. Four time slices of a 3D geophysical model, between 5-10 cm up to 30-40 cm in depth, of the clayey soil study site, located in the facility of the Military Unit of Serra do Pilar, Vila Nova de Gaia. In each time slice, arrows indicate regions where signals could be correlated with target's positions.

Table 5. Percentages of explosive devices detection, buried at the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, Porto, Portugal, using the results obtained with the 2D-Easyrad (1)) and 3D-Radar (2)) on the sandy and on the clayey soil: a) average for each frequency antenna using the results obtained at Spring and Autumn; b) in each season with both antennas used; c) average in each soil type; d) average for different explosive devices casing material and e) burial depths (-=scans not performed; n/a=not applicable; *n=1; #n=2; +n=4).

		Sandy soil		**Clayey soil**		**Sandy soil**	**Clayey soil**
		1) 2D-Easyrad				**2) 3D-Radar**	
		300 MHz	**100 MHz**	**300 MHz**	**100 MHz**	**n/a**	
a) Antenna frequency (average)		#40.00%	#20.00%	#54.50%	#4.50%	-	
b) Environmental conditions	Spring	*60.00%	*30.00%	*64.00%	*9.00%	-	
	Summer	*60.00%	-	*64.00%	-	-	
	Autumn	*20.00%	*10.00%	*45.00%	*0.00%	-	
	Winter	*50.00%	-	*54.00%	-	*100.00%	*100.00%
c) Soil type (average)		+47.50%	#20.00%	+56.75%	#4.50%	*100.00%	*100.00%
d) Type of casing material (average)	Metal	+66.67%	#25.17%	+58.33%	#8.50%	*100.00%	*100.00%
	Plastic	+8.33%	#16.67%	+56.25%	#0.00%	*100.00%	*100.00%
	Wood	+50.00%	#0.00%	+50.00%	#0.00%	*100.00%	*100.00%
e) Depth of burial (average)	5 cm	+37.50%	#25.00%	+25.00%	#0.00%	*100.00%	*100.00%
	15 cm	+58.33%	#33.33%	+91.67%	#0.00%	*100.00%	*100.00%
	30 cm	+45.00%	#10.00%	+50.00%	#8.50%	*100.00%	*100.00%

Table 6. Percentages of detection, obtained in each season of the year, on the sandy and on the clayey soil, at the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, Porto, Portugal, using the 2D-Easyrad and both frequency antennas (300 and 100 MHz), for the different explosive devices casing material (EDs=explosive devices; -=scans not performed; *n=1; ^n=3; &n=4; =n=6).

	Sandy Soil					
	300 MHz			**100 MHz**		
	=Metal EDs	**^Plastic EDs**	***Wood EDs**	**=Metal EDs**	**^Plastic EDs**	***Wood EDs**
Spring	100.00%	0.00%	0.00%	33.33%	33.33%	0.00%
Summer	83.33%	0.00%	100.00%	-	-	-
Autumn	33.33%	0.00%	0.00%	17.00%	0.00%	0.00%
Winter	50.00%	33.33%	100.00%	-	-	-

	Clayey Soil					
	300 MHz			**100 MHz**		
	=Metal EDs	**&Plastic EDs**	***Wood EDs**	**=Metal EDs**	**&Plastic EDs**	***Wood EDs**
Spring	66.67%	50.00%	100.00%	17.00%	0.00%	0.00%
Summer	66.67%	75.00%	0.00%	-	-	-
Autumn	50.00%	50.00%	0.00%	0.00%	0.00%	0.00%
Winter	50.00%	50.00%	100.00%	-	-	-

Table 7. Percentages of detection, obtained in each season of the year, on the sandy and on the clayey soil, at the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, Porto, Portugal, using the 2D-Easyrad and both frequency antennas (300 and 100 MHz), for the different explosive devices' burial depths (EDs=explosive devices; -=scans not performed; *n=2; ^n=3; &n=5; =n=6).

	Sandy Soil					
	300 MHz			**100 MHz**		
	***EDs buried at 5 cm**	**^EDs buried at 15 cm**	**&EDs buried at 30 cm**	***EDs buried at 5 cm**	**^EDs buried at 15 cm**	**&EDs buried at 30 cm**
Spring	50.00%	66.67%	60.00%	50.00%	33.33%	20.00%
Summer	50.00%	66.67%	60.00%	-	-	-
Autumn	50.00%	33.33%	0.00%	0.00%	33.33%	0.00%
Winter	0.00%	66.67%	60.00%	-	-	-
	Clayey Soil					
	300 MHz			**100 MHz**		
	***EDs buried at 5 cm**	**^EDs buried at 15 cm**	**=EDs buried at 30 cm**	***EDs buried at 5 cm**	**^EDs buried at 15 cm**	**=EDs buried at 30 cm**
Spring	0.00%	66.67%	83.33%	0.00%	0.00%	17.00%
Summer	50.00%	100.00%	50.00%	-	-	-
Autumn	0.00%	100.00%	33.33%	0.00%	0.00%	0.00%
Winter	50.00%	100.00%	33.33%	-	-	-

V. DISCUSSION

The use of the ground penetrating radar (GPR) to detect buried explosive devices (EDs) has seen successful results, however, this is a complex task since many factors can affect its detection capability. Due to such issue, in the present field study it was intended to evaluate the feasibility of GPR use on the detection of buried inert EDs, towards five different variables: frequency of operation, environmental conditions, soil type, ED casing materials and target's burial depth, also comparing the efficiency of two different GPR systems (2D versus 3D). However, it seems important to highlight that the used EDs did not have explosive content inside of them, being inert. Thus, GPR signals may not be total representative of the ones that can be obtained in real scenarios (VanderGaast *et al*., 2015). Furthermore, the obtained percentages of detection could be higher if performing additional GPR scans, parallel to the y direction of both study sites (Figs. 22 and 23), which means, scans perpendicular to the ones that were performed. This would allowed the obtention of the strongest potential signal from the targets (Watters and Hunter, 2004), since if targets are buried parallel to the scans direction, the signal is expectably stronger due to a larger reflection surface (Núñez-Nieto *et al*., 2014).

The following discussion was structured accordingly to the different studied variables.

5.1.EFFECT OF DIFFERENT GPR FREQUENCY ANTENNAS

Two different 2D-Easyrad antennas, from those available (100, 200 and 300 MHz), were selected: a medium frequency antenna of 300 MHz, and a lower frequency antenna of 100 MHz.

Relatively to their hand-held operation during surveys, the 2D-Easyrad with the 300 MHz antenna was much easier to manipulate due to its smallest size, being the intended (Scheers, 2001). In fact, the use of smaller antennas (high frequency) results in better mobility and lower antenna-target interactions, being suitable for UXOs and landmines detection (Youn and Chen, 2005).

Comparing the percentages of EDs detection obtained with both antennas (Table 5), it is clear that for shallow subsurface investigations, higher frequencies allow obtaining better results, mainly due to the enhance in image resolution (Daniels, 2007). The same was stated by Metwaly (2007) that worked with three different frequencies in a sandy soil (400 MHz, 900 MHz and 1500 MHz), having seen that increasing the antenna frequency, the resolution and amplitude of the reflected signals were consequently enhanced, although attenuation could also increase. Hansen and Pringle (2013) also found that if using higher frequencies (900 MHz versus 450 MHz), better GPR performance is obtained towards the detection of buried forensic objects in semi-urban and patio environments. In other work, where two different frequency antennas (1 GHz and 2.3 GHz) were used to detect buried EDs (mines, projectiles and mortars) in a sandy soil, at depths similar to those that were used in the present field study, it was found that the higher frequency antenna allowed for better visualization of the target reflection patterns (Núñez-Nieto *et al*., 2014). Contrary to all of the previous presented data, Dionne (2007) found better GPR results for forensic targets detection when using the lower frequency (500 MHz versus 800 MHz), showing the importance of taking into account the specific targets and the study site characteristics when choosing the optimal frequency of operation.

With the 100 MHz frequency antenna, although the much lower percentages of detection, one of the smaller targets was detected (instruction hand grenade Mod/962 in the Spring season, in the sandy soil study site), which was not likely due to the low image resolution of the data obtained with this frequency. With this antenna, contrary to the 300 MHz, the higher percentages of detection were obtained in the sandy soil study site (Table 5). Since this antenna has lower radar resolution, and the clayey soil study site was more heterogeneous, maybe signals from the inert EDs and adjacent stones/ roots were not efficiently differentiated (Sato, 2009), resulting in lower detection performance in this soil type.

The antenna frequencies for explosive devices detection used in previous studies are normally higher than the ones used in the present study with the 2D-Easyrad (Chlaib *et al*., 2014; Metwaly, 2007; Núñez-Nieto *et al*., 2014). As the targets were buried at shallow depths, with a maximum of 30 cm, the use of higher frequencies could have resulted in higher percentages of detection due to the enhance in image resolution. However, since in real scenarios it cannot be predict, with total certainty, the depth at which targets were buried, the use of low frequencies can be initial preferred to guarantee that, at least, something is detected (Scheers *et al*., 1998).

5.2. EFFECT OF ENVIRONMENTAL CONDITIONS AND SOIL TYPE

The capability of GPR detection were evaluated during the four seasons of the year, in two different soil types, a sandy soil and a clayey soil. Since changes in environmental conditions will greatly affect the soil properties, these two variables will be discussed together.

The different climatic conditions, as well as the different characteristics of the host material in where an object is buried, in this case soil, have an effect on GPR detection performance, as stated in previous field studies and literature (Abeynayake and Tran, 2016; Druyts *et al*., 2011; Van Dam *et al*., 2013), controlling significantly the propagation of electromagnetic (EM) waves.

Different soil types will consequently have different electromagnetic properties. In literature it is stated that GPR technology used in clayey soils will produce poor data (Baker *et al*., 2007; Pringle *et al*., 2015), whilst sandy soils, on the other hand, are usually considered an optimum propagation medium for GPR surveys, which will however always depend on the specific survey site characteristics (Pringle *et al*., 2012). This poor performance outcomes from higher electrical conductivity in soils with increased clay particles content, resulting in attenuation of EM waves, thus limiting their propagation depth (Griffin and Pippett, 2002). In the present study, however, higher percentages of EDs detection were obtained in the clayey soil type with the 300 MHz antenna (Table 5). Since the targets were buried at shallow depths, maybe the content of clay particles had not been enough to affect the GPR detection performance. On the other hand, the clayey soil study site showed more inhomogeneities, specially roots and stones, that could have originate signals in the GPR images of the 300 MHz antenna later mistaken as buried targets due to possible similar responses (Marques *et al*., 2012; Solla *et al*., 2012). With the 100 MHz antenna, contrary to this, the higher percentages of detection were obtained in the sandy soil (Table 5). Since this antenna has lower radar resolution, and the clayey soil study site was more heterogeneous, like previous mentioned, maybe signals from the inert EDs and adjacent stones/ roots were not efficiently differentiated (Sato, 2009), resulting in lower detection performance in this soil type.

In relation to the environmental conditions, an increase in soil water content will tend to enhance the host medium attenuation properties (Daniels, 2007) that may cause difficulty in the detection of buried targets. When comparing the percentages of EDs detection obtained for both study sites, with both antennas, in the dry seasons (Spring and Summer) with those in the rainier seasons (Autumn and Winter; Table 5), it is seen a decay in GPR detection capability in both soil types, which is normally expected due to the enhance in EM waves attenuation. Models for prediction of radar responses under different soil conditions were purposed by Miller *et al*. (2004), and the effect of an increase in soil water content was evaluated in field soils. As in the obtained results, it was seen a global decrease in radar image quality after clayey soils water content increased. However, for a sandy soil, it is stated that the effect of the increase in water content can be different depending on the landmine being metallic (poor detection) or non-metallic (better detection), which is later discussed in section 5.3.

Since it rained in the morning of the Autumn surveys, soils could be saturated with water, contributing to a huge increase in soils conductivity, which can explain the lowest percentages of EDs detection obtained in this season for both soil types. The same was concluded in a work where, although using a GPR operating at frequencies below 500 MHz, even a 155 mm artillery shell could not be reliably detected probably due to the high moisture content of the study site (Altshuler *et al*., 1995). In the Winter survey, a season where normally rains a lot, the results obtained did not match with those expected, being anticipated the lowest percentages of EDs detection to this season. However, no rain occurred previously in that day.

The organic control, represented in the present work by a raw chicken, was only detected in all seasons, in the sandy soil study site, being in accordance with previous studies of pig carcasses also buried in a sandy and a clayey soil (Schultz, 2008; Schultz *et al*., 2006). The higher content of clay particles can lead to the approximation of dielectric permittivity value between the organic body and the surrounding soil (Schultz *et al*., 2006), consequently masking the signal from the chicken remains.

The use of empty holes is important for allowing to see that the signal received on the other targets is not only due to disturbed soil (Dionne, 2007).The negative control of the present work, was only observed in radargrams obtained in the sandy soil, in the Spring and Summer surveys, which can possibly indicate that this type of soil needs more time to compact than the clayey soil. Due to that, it cannot be said with complete certainty that the signals detected with the GPR in those season surveys were only due to the EDs and not also due to the presence of air on the subsurface, anthropogenically incorporated while burying the targets. However, these are still useful results, since it proves that even if the target itself cannot be detected, at least it can be detected, during a certain period, the soil disturbances caused by its burial.

5.3.EFFECT OF EXPLOSIVE DEVICE CASING MATERIALS

The type of buried targets, especially their casing materials, can influence their detection by GPR. To evaluate the effect of this variable, at least one representative of an explosive device with metal, plastic and wooden casing was buried.

The metal targets have high dielectric permittivity and conductivity (Fachbereich, 2013), allowing their relatively easy detection in a variety of soil types (Miller *et al*., 2002). In both study sites, using both antennas, the higher average percentage of detection was obtained for the EDs with metal casing (Table 5), probably explained by the higher contrast of the properties (Núñez-Nieto *et al*., 2014). Consistent with these results, were the results obtained by Hara and Hirose (2004), showing that plastic mines are more difficult to be detected than metal devices, although using much higher frequency antennas. Chlaib *et al*. (2014) also found that an iron box is better detected than a plastic and wooden box, having higher reflection values. Observing the percentages of detection during the four seasons with the 300 MHz antenna for the metal objects, it was observed that an increase in the soils water content (corresponding to the rainy seasons Autumn and Winter), resulted in a decreased detection (Table 6), being consistent with previous works where the effect of moisture content in GPR detection capability is evaluated (Fachbereich, 2013; Miller *et al*., 2004).

There is some literature suggesting that, in very arid ground, plastic mines are more difficult to be detected due to reduced dielectric contrast between the explosive device and the host soil, since both, dry sand and plastic objects, have low dielectric permittivity and conductivity (Metwaly *et al*., 2006; Miller *et al*., 2002). However, an increase of water content in sandy soils would allow plastic mines to be easily detected (Daniels, 2009; Miller *et al*., 2004), since water leads to an enhance in soils dielectric permittivity, while this value remains low for the plastic object, enhancing the contrast (Griffin and Pippett, 2002; Miller *et al*., 2002). This previous literature is in accordance with the results obtained with the 300 MHz antenna, since inert EDs with plastic casing, buried in the sandy soil, were only detected in the Winter survey, where it was expected to occur an increase in soil water content, although only one could be noticed (Table 6). For the same reason, plastic explosive devices were also expected to be detected at the Autumn survey, however, maybe due to the heavy rain in the survey morning, EM waves suffered huge attenuation and a lot of targets could not be detected, including the plastic ones. Using the 100 MHz frequency in the sandy soil type, also only one plastic explosive device could be detected, although it was in the Spring survey (Table 6), which was not expected.

Contrary to the sandy soil type, clayey soils have higher conductivity, due to the high content in clay particles, allowing for an easy detection of plastic objects. In fact, in the clayey soil study site, the EDs with plastic casing were much more easily detected with the 300 MHz antenna, with an average percentage of detection of 56.25% (Table 5), which is explained by the higher contrast of EM properties (Griffin and Pippett, 2002). On the other hand, with the 100 MHz antenna, the plastic EDs were not detected in this soil type (Table 5). The increase in clayey soils water content did not had the same effect as in the sandy soil towards the detection of plastic EDs, with percentages of detection not being enhanced, which was also found in the work of Miller *et al*. (2002; 2004). In fact, in the present study, the higher percentage of detection of plastic EDs in the clayey soil were obtained in a dry season (Summer; Table 6).

Finally, concerning the wooden material, only one representative explosive device was buried, the improvised explosive device (IED) in a wooden box. This target, using the 300 MHz antenna, was detected in Summer and Winter surveys, in the sandy soil and in Spring and Winter surveys, in the clayey soil (Table 6), suggesting that neither the soil type nor the environmental conditions had a direct effect on its detection. Nevertheless, both were not able to detect the wooden ED in the Autumn season, when soils were possibly saturated with water due to the rain. Similar results were obtained in the work of Hasan and Fenning (1990), where wooden coffins, buried in a wet clayey soil were not detected, using a GPR with frequency antennas of 900, 500 and 100 MHz. Coffins were probably saturated with water, contributing to no contrast of physical properties (Pye and

Croft, 2004). With the 100 MHz antenna the wooden target was also not detected, in none of the soils (Table 5).

5.4. EFFECT OF DIFFERENT EXPLOSIVE DEVICES' BURIAL DEPTHS

To evaluate the effect on GPR detection related to burial depths, EDs were buried at 5, 15 or 30 cm, depending on the depths in which they are normally encountered (Denefeld *et al*., 2017; Yip *et al*., 2015).

Explosive devices buried at 5 cm below the ground surface were more difficult to be detected in both soil types when using the 300 MHz antenna, having the lowest average percentage of detection (Table 5), maybe due to the strong interference caused by direct waves transmitted between both antennas and reflection from the ground surface (Hara and Hirose, 2004), masking the target's reflected signals (Scheers, 2001). On the other hand, since the targets buried at 5 cm were the two hand grenades, being the smallest used objects, the lowest percentage of detection can also be due to their reduced size. Observing the percentages of detection at each season survey, with the 300 MHz frequency, the environmental conditions did not seem to affect the detection of targets buried at 5 cm, since in the sandy soil, the percentage of detection were the same at Spring, Summer and Autumn, and in the clayey soil the same percentage of detection were obtained at Spring and Autumn (0.00%) and at Summer and Winter (50.00%; Table 7).

The targets buried at 30 cm below the ground surface, although easier detected than those buried at 5 cm, showed lower average percentage of detection when compared with the targets buried at 15 cm and when using the 300 MHz antenna (Table 5), which can be explained by the fact that, increasing the burial depth, energy losses in the soil also increases and a smaller portion of the transmitted waves arrives at the landmine (Montoya and Smith, 1999). It was also observed that the percentages of detection of the targets buried at 30 cm, with the 300 MHz antenna, decreased from the dry seasons (Spring and Summer) to the rainy seasons (Autumn and Winter), especially in the clayey soil study site (Table 7). This fact can be a result of reduced waves maximum penetration depth, due to an enhance in soil water content (Bhuiyan and Nath, 2006), being wave attenuation more evident in clay rich soils (Griffin and Pippett, 2002). Richardson and Cheetham (2013) also saw that, using a GPR with a 500 MHz antenna frequency, to detect buried weapons, strong signals were obtained from more targets when they were buried at 10 cm than when buried at 30 cm or 50 cm, being the depth more approximate to the depth where the best results were obtained in the present study (15 cm).

With the 100 MHz frequency antenna, results were not consistent between sandy and clayey soil, contrary to the obtained with the 300 MHz antenna. In the sandy soil, although it was seen a better detection of the targets buried at 15 cm (Table 5), similar to the obtained with the 300 MHz antenna, the average percentage of detection of the targets buried at 5 cm was higher than the obtained in targets buried at 30 cm. This result was not expected since lower frequency antennas can accomplish higher penetration depths (Schultz *et al*., 2013), being more likely an easier detection of targets buried at greater depths. In the clayey soil type, the expected results were obtained, since the only detected target was at 30 cm below ground surface (Spring survey; Tables 5 and 7).

5.5. 2D-EASYRAD VERSUS 3D-RADAR

Two different GPR systems were compared in the Winter survey to evaluate their feasibility to detect buried explosive devices: the 2D-Easyrad, using the 300 MHz antenna, and the 3D-Radar.

First, in terms of their operation mode, some clear differences can be pointed out. Although 3D-Radar can be mounted in a vehicle, both were used as hand-held systems, being the 2D-Easyrad, due to its lower size and weight, much easier to handle during surveys, being ideal for sites of difficult access. However, the time required to perform the GPR scans in both study sites was less with the 3D-Radar comparing with the 2D-Easyrad, which makes the 3D-Radar more suitable to perform surveys in large areas.

Comparing the results obtained with the 2D-Easyrad (frequency antenna of 300 MHz) and the 3D-Radar, both in the Winter survey, much higher percentages of detection were obtained with the 3D-Radar, reaching 100.00% in both study sites (Table 5). Besides other distinctions, the frequency coverage may be the primarily responsible for this difference in detection capability. While the 2D-Easyrad, using an antenna with a centre frequency of 300 MHz, can only have a total frequency coverage of 10 MHz up to 500 MHz, the 3D-Radar can have a frequency coverage of 100 MHz up to 3 GHz, with the advantage of using a step-frequency technique (Fig. 9), allowing to take advantage of both low and high frequencies. As previous stated in section 5.1, and verified with these results, the use of higher frequencies can, in fact, enhance the capability of GPR detection towards explosive devices buried at shallow depths.

Although all targets were detected with the 3D-Radar, an overall stronger response from the metal buried explosive devices, comparing with the ones with plastic casing, was observed, being in agreement with literature (Núñez-Nieto *et al*., 2014). This is probably due to the high dielectric constant of metal when compared with plastic, resulting in higher amplitude reflected signals (Chlaib *et al*., 2014), as also stated in the discussion of the results obtained with the 2D-Easyrad (section 5.3). The IED in a wooden box was easily detected in both soils with both GPRs in the Winter, with a percentage of detection of 100.00% (Tables 5 and 6), with a correspondent strong 3D GPR signal. Consistent with these results, were the results obtained in a previous study where an antenna with a centre frequency of 1.5 GHz was used to detect buried iron and plastic and wooden boxes, being all targets also detected, with different signal strengths (Chlaib *et al*., 2014). Concerning the organic control, the 2D-Easyrad was only able to detect it on the sandy soil study site. Although literature suggest that this type of target is more difficult to be detected when buried in a clayey soil, as stated in section 5.2, the 3D-Radar was able to detect it on both soil types. Relatively to the negative control, this target was not detected with the 2D-Easyrad. With the 3D-Radar, it was detected in both soils, although not being expected due to the long period of time passed between the burial and the GPR survey. As previously stated, this result prevents the exclusion of the possibility that signals could also be from air incorporated in the subsurface at the time of burial.

Concerning the depth at which targets were buried, with the 2D-Easyrad in the Winter season, those buried at 15 cm were the most easily detected on both soil types, while the least detected where the targets buried at 5 cm on the sandy soil and at 30 cm on the clayey soil study site (Table 7). With the 3D-Radar all of the targets were detected (100.00% for all burial depths), being able to easily detect even the two hand grenades that were buried at only 5 cm below the ground surface, due to its capacity in obtaining maximum resolution at shallow depths

(Eide and Hjelmstad, 2004). Regarding the depths at which targets were detected in the four time slices of the 3D geophysical models, it does not correspond exactly to their burial depth. This could be attributed to a wrong velocity selection for depth conversion. Furthermore, since almost a year has passed after the target's burial, targets could have been slightly moved being influenced by the rain action during the burial period.

Finally, although expected due to the high-resolution of the radar images obtained with the 3D-Radar, discrimination and identification of the different explosive devices was not possible, similarly to the 2D-Easyrad, being only possible to detect their presence. This classification however would be important since different types of explosive devices require specific clearance protocols (Gersbeck, 2014). For this, the development of algorithms for targets discrimination have shown promising results (Daniels *et al*., 2008; Lopera *et al*., 2007; Sakaguchi *et al*., 2017; Sun *et al*., 2005).

VI. CONCLUSIONS

The main aim of the present work was to study the feasibility of the ground penetrating radar (GPR) on the detection of buried inert explosive devices, using a 2D GPR, the 2D-Easyrad, concerning variables, known in literature, that can affect GPR data: frequency of operation, environmental conditions, soil type, type of casing material and burial depth. Furthermore, the comparison between a 2D and a 3D system was later also intended.

The results obtained with both antennas showed that 2D-GPR performance towards the detection of buried explosive devices is better when using the higher frequency and when under good environmental conditions (Spring and Summer).

Additionally, and contrary to what is stated in literature, with the 300 MHz antenna, better detection capacity was obtained in the clayey soil type, while with the 100 MHz better performance was achieved in the sandy soil, as normally assumed. Concerning the casing material, explosive devices with metal casing where the most easily detected in both soil types with both used antennas, having higher amplitude reflection signals. The explosive devices with plastic and wood casing were also easily detected in the clayey soil type with the 300 MHz antenna. In terms of the effect of the different burial depths, those buried at 15 cm were the easiest detected, in both soils, using the 300 MHz antenna. With the 100 MHz antenna, the targets buried at 15 cm were also the easiest detected in the sandy soil, while in the clayey soil the easiest detected targets were the ones buried at 30 cm. With the 3D-Radar, all buried targets were detected in both soils and considering all variables, showing the advantage of using higher frequencies and a step-frequency approach, although having received stronger signals from the metal explosive devices. Although detected, explosive devices could not be identified based on the 2D and 3D obtained data.

According to the obtained results it can be concluded that the use of GPR technology is feasible to detect both metallic and non-metallic buried explosive devices, being however greatly affected by the soil properties and environmental conditions, the 2D system being most affected. Furthermore, it was seen that the choice of an adequate frequency of operation and type of GPR system is preponderant for a successful subsurface investigation, being necessary to consider the environmental conditions, the specific soil properties and the context of the burial (type of target and presumed burial depth).

For future studies, an extended comparison between the use of the 2D-Easyrad and the 3D-Radar is intended, in order to better understand the feasibility differences between both systems, including the effect that environmental conditions have on the 3D-Radar. 3D method optimization is also a future aim, so that the ideal settings to identify different targets using the 3D-Radar can be defined. Furthermore, to eliminate biased results, and to approach more closely to what happens in real case scenarios, the performance of blind tests is also aimed. Additionally, it would be extremely important to implement more training studies in controlled study sites, where careful measurements of the relevant soil properties are performed prior to the surveys, allowing better understanding of the effect that specific soil properties (*e.g.* conductivity, texture, moisture content) have on GPR performance, as well as more reliable comparisons with previous works. This type of studies will allow the development of standardized protocols, which are essential for the successful use of geophysical surveys in forensic and military investigations.

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VIII. ATTACHMENTS

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Testing a 2D Ground-penetrating radar towards the detection of explosive targets buried in Portuguese soils

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Testing a 2D Ground-penetrating radar towards the detection of explosive targets buried in Portuguese soils

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Abstract— **Many scientist groups have been working in the development of geophysical methods that enable more secure and efficient ways of explosive devices detection for subsequent clearance. Ground penetrating radar (GPR) has been showing promising results. In the present study it was intended to evaluate the feasibility of inert explosive devices detection, namely landmines, improvised explosive devices and unexploded ordnance, using a 2D GPR system: 2D-Easyrad. Furthermore, it was intended to assess the effect that different GPR frequency antennas, environmental conditions, types of soil, types of casing materials and burial depths have on the capacity of GPR detection. Therefore, using two GPR antenna frequencies (300 MHz and 100 MHz), scans were performed during one year, encompassing the four seasons, on two different soil types (sandy and clayey), In the two test sites, wooden, plastic and metal enclosured explosive devices were buried at different depths (5 cm, 15 cm or 30 cm). Parallel scans were performed along the test site´s length, spacing 0.2 m (300 MHz antenna) or 0.4 m (100 MHz antenna). Results showed that all these variables affect GPR detection efficiency, with better results being obtained when using higher antenna frequencies, under good environmental conditions (Spring and Summer), when applied in the clayey soil type and when detecting metal targets and targets buried at depths of 15 cm.**

Index Terms— **Forensic Geophysics, GPR, IED, UXO**

I. INTRODUCTION

THE problematic of buried explosive devices, which includes unexploded ordnance (UXO) and improvised explosive devices (IEDs), is not new, with many countries facing this issue throughout the last decades, resulting in high numbers of civilians and soldiers deaths and injuries [1]. This reality led, in 1997, to the creation of the "Convention on the prohibition of the use, stockpiling, production and transfer of anti-personnel mines and on their destruction", which in 2018 had 164 State Parties, including Portugal [2]. Annual landmine monitors have been made since 1999, where global tracking's are presented. Two years ago, in 2017, they recorded a total of 7.239 casualties in 49 countries due to landmines/explosive remnants of war (ERW), and the highest numbers of fatalities caused by IEDs (2.716) and of child victims (2.452), since the beginning of this annual monitoring [2]. Therefore, the detection and removal of these deadly devices is mandatory. However, even the process of demining is not simple and peaceful, with nearly two deminers being killed for every 1000 mines removed, as stated in the United Nations (UN) statistics [3].

Geophysical techniques have been applied on buried explosive devices detection, being the ground penetrating radar (GPR) recognized as a promising technique [4], aiming to enhance the efficiency of demining operations, also decreasing the associated hazards of these process. The GPR works through emission of electromagnetic (EM) radio waves, that are reflected back to the surface due to an existing subsurface anomaly, like a buried object, leading to their consequent detection [5]. The characteristics of the reflected signal, specially their magnitude, will depend mostly on the contrast of EM properties, mainly dielectric permittivity and conductivity, between the host material and the buried object. Thus, the greater the contrast, easier the detection [6].

Despite having some limitations, like a high rate of false positives due to the presence of natural ground clutter (e.g. roots and rocks), GPR technology has been successfully used in a wide range of soil types and environmental conditions. Moreover, it can detect both metallic and non-metallic targets [7], unlike the commonly used metal detectors, which is an advantage due to the crescent number of minimum-metal and plastic mines.

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Some sophisticated radar methods for explosive devices detection have been used, however, when applied to real field scenarios, apart from the laboratory, few of them proved to be really efficient [8]. Explosive devices can have different shapes, sizes and casing materials, being found in desert regions, jungles or urban areas, at various depths [8]. Therefore, the equipment for explosive devices detection needs to work in a huge variety of soil and climatic conditions [9], enhancing the importance of performing field studies.

In this work the capacity that a 2D-GPR has in detecting buried explosive targets was tested, evaluating five possible existent variables: GPR antenna frequency (300 MHz and 100 MHz), different environmental conditions (Spring, Summer, Autumn and Winter), soil types (sandy and clayey), type of explosive device casing materials (wood, plastic, and metal) and depth of burials (5, 15 and 30 cm).

II. MATERIAL AND METHODS

A. Test site and GPR surveys

The present field study was performed during the Spring, Summer, Autumn and Winter of 2018-2019, being the test site located inside a facility of the Military Unit of Serra do Pilar, a former Artillery Regiment Unit (41º14'N, 08º60'W), in the city of Vila Nova de Gaia, Porto, Portugal. Inside the facility, two test-sites, with different soil types (sandy (Fig. 1) and clayey (Fig. 2)), both having an area of 27 m2 (3 m x 9 m), were selected and cleaned up, due to their intense vegetation. Posteriorly, aiming to define the burial positions, a grid was designed along both areas, using wooden sticks and measure tape, resulting in a total of 27 squares (1 m x 1 m). Then, a total of 10 inert explosive devices were buried in the sandy soil and 11 similar inert explosive devices were also buried in the clayey soil. A negative control (empty hole) and an organic control (chicken) were implemented on both soils (Table I). From the 10 inert explosive devices buried in the sandy soil, 1 had a wooden casing, 3 a plastic casing and 6 a metal casing, being 2 buried at 5 cm, 3 at 15 cm and 5 at 30 cm. From the 11 explosive devices buried at the clayey soil 1 had a wooden casing, 4 a plastic casing and 6 a metal casing, being 2 buried at 5 cm, 3 at 15 cm and 6 at 30 cm.

GPR scans were performed using two frequency antennas of a GPR system 2D-Easyrad (Fig. 3): 300 MHz and 100 MHz, in each season of the year and on both soils. The 2D-Easyrad, used with these antennas, can have a frequency bandwidth of 10 MHz to 500 MHz and a time window of 75 or 150 ns, which determine how deep the radar system will investigate the subsurface [10]. The antenna with a central frequency of 300 MHz has a value for both horizontal and vertical resolution of 0.3 m while these values for the antenna with a central frequency of 100 MHz are of 0.5 m [11]. The 300 MHz GPR antenna was used at each season survey, performing parallel scans to the test sites length (9 m), spaced by 0.2 m along the y direction, and the 100 MHz GPR antenna was used only at Spring and Autumn season surveys, performing parallel scans to the test sites length (9 m), spaced by 0.4 m along the y direction.

B. GPR data processing

The raw data were imported as individual radargrams to the Reflex-Win program. When importing the radargrams, the x and y value were defined, corresponding the x value to the total length of each radargram (0 to 9 m in the clayey soil and 0.6 to 8.4 m in the sandy soil), and the y having cumulative values of 0.2 m for the 300 MHz antenna frequency, and of 0.4 m for the 100 MHz antenna frequency. Then, the time window was defined previously to the data processing, being of 75 ns, and the velocity for both mediums were specified at 0.11 m/ ns, resulting in radargrams with a total depth of approximately 4 m.

GPR images can be frequently influenced by clutter or background noise originated, for example, by the presence of stones, the existence of highly irregular stratigraphic boundaries or even from the direct wave that is directly transmitted between transmitter and receiver antennas [12]. If the signal of these secondary reflections is too strong, it can obscure the signal from the buried targets, being the reduction of the ground clutter, the most important pre-requisite for a resulting good quality GPR image interpretation. Thus, finally, each individual radargram was processed using the following methodology [13], [14]:

1. Subtract-mean (Dewow): to remove the very low frequencies, resulting in an image with a more equilibrated colour scale;
2. Background Removal: applied to all window travel time, resulting in the enhancement of subsurface signals due to the removal of the first and stronger signals from ground surface reflection and from direct waves transmitted between antennas;
3. Bandpass Butterworth between 30 MHz and 400 MHz: with the aim of removing any frequency below or above the specified interval, resulting in a clearer image with enhancement of signals from potential buried targets;
4. Running average: that automatically performs the average every two traces, resulting in an image with better resolution and consequently stronger enhancement of signals from subsurface targets.

Results were presented in the format of 2D-radargrams, where the total length of the test sites as a function of the travel time (ns)/ depth(m), for individual horizontal line scans, was represented.

C. GPR data assessment

GPR profiles, from both soil types, were compared with the target burial positions (Fig. 1; Fig. 2; Table I), and possible signals from the explosive devices (ED) were analysed. The percentage of explosive devices detection was calculated for each of the used antennae, at each season survey. Furthermore, the percentage of detection in terms the type of casing material and burial depth, considering the total number of buried EDs, was also assessed.

III. RESULTS

Due to the large quantity of data, only some GPR profiles, with expressive and possible target signals, are presented.

A. Spring survey

A.1. At the sandy soil type, using the 300 MHz frequency antenna, hyperbole shape signals could be correlated with the EDs identified with the numbers 5, 6, 7 (Fig. 4), 8, 9, and 11 (Fig. 1; Table I). Thus, a total percentage of EDs detection of 60.00% was obtained, being 6 metal EDs (100.00%); 1 buried at 5 cm (50.00%), 2 at 15 cm (66.67%) and 3 at 30 cm (60.00%; Table II). With the 100 MHz antenna frequency, detected signals could be correlated with the EDs identified with the numbers 4, 7 (Fig. 5), and 11 (Fig. 1; Table I), corresponding to a percentage of detection of 30.00%, being 2 metal EDs (33.33%) and 1 plastic ED (33.33%); 1 buried at 5 cm (50.00%), 1 at 15 cm (33.33%) and 1 at 30 cm (20.00%; Table II).

A.2. At the clayey soil, with the 300 MHz frequency antenna, hyperbolic shape signals could correspond to the EDs identified with the numbers 1, 3, 6 (Fig. 6), 8, 10, 12, and 13 (Fig. 6; Fig. 2; Table I), obtaining a percentage of detection of 64.00%, being 1 wooden ED (100.00%), 2 plastic EDs (50.00%) and 4 metal EDs (66.67%); 2 buried at 15 cm (66.67%) and 5 buried at 30 cm (83.33%; Table II). With the 100 MHz antenna, it was only detected a GPR signal that could correspond to the EDs identified with the number 12 (Fig. 7; Fig. 2; Table I), equivalent to a total percentage of detection of 9.00%, being a metal ED (17.00%) buried at 30 cm (17.00%; Table II).

B. Summer survey

B.1. In the radargrams of the sandy soil type, hyperbolic shape signals could be correlated to the EDs identified with the numbers 3, 5, 6 (Fig. 8), 7 (Fig. 8), 8, and 11 (Fig 1; Table I). A total percentage of detection of 60,00% was obtained, being detected the only ED with wooden casing (100.00%) and 5 with metal casing (83.33%); 1 buried at 5 cm (50.00%), 2 at 15 cm (66.67%) and 3 at 30 cm (60.00%; Table II).

B.2. At the clayey soil type, it were possibly detected the EDs identified with the numbers 1 (Fig. 9), 4, 6, 7, 10 (Fig. 9), 12, and 13 (Fig. 2; Table I), resulting in a total percentage of detection of 64.00% (Table II). Relating to the casing material and depth of burial, it were detected 3 plastic EDs (75.00%) and 4 metal EDs (66.67%); 1 buried at 5 cm (50.00%), 3 at 15 cm (100.00%) and 3 at 30 cm (50.00%; Table II).

C. Autumn survey

C.1. At the sandy soil type, with the 300 MHz frequency antenna, hyperbolic shape signals could correspond to the EDs identified with the numbers 5 and 6 (Fig. 10; Fig. 1; Table I), providing a total percentage of detection of 20.00%, being 2 metal EDs (33.33%); one buried at 5 cm (50.00%) and the other at 15 cm (33.33%; Table II). With the 100 MHz frequency antenna, it was possibly detected only 1 ED identified with the number 7 (Fig. 11; Fig. 1; Table I), corresponding to a total percentage of detection of 10.00%, being a metal ED (17.00%) buried at 15 cm (33.33%; Table II).

C.2. At the clayey soil type, with the 300 MHz frequency antenna, it were possibly detected signals corresponding to the EDs identified with the numbers 1 (Fig. 12), 6 (Fig. 12), 7, 12, and 13 (Fig. 12; Fig. 2; Table I), corresponding to a total percentage of detection of 45.00% (Table II). Concerning the casing material, it was possible to detect 2 plastic EDs (50.00%) and 3 metal EDs (50.00%); 3 buried at 15 cm (100.00%) and 2 at 30 cm (33.33%; Table II). At this season of the year, the 100 MHz frequency antenna were not able to detect any buried ED.

D. Winter survey

D.1. At the sandy soil, GPR signals could be correlated with the presence of the EDs identified with the numbers 2, 3, 6 (Fig. 13), 7, and 9 (Fig. 1; Table I). The total percentage of detection was 50.00%, being detected 1 wooden ED (100.00%), 1 plastic ED (33.33%) and 3 metal EDs (50.00%); 2 buried at 15 cm (66.67%) and 3 at 30 cm (60.00%; Table II).

D..2. At the clayey soil it were possibly detected the EDs identified with the numbers 1, 3 (Fig. 14), 5, 6, 7 (Fig. 14), and 13 (Fig. 2; Table I), resulting in a total percentage of detection of 54.00% (Table II). Concerning casing material and burial depth, it was detected the only wooden ED (100.00%), 2 plastic EDs (50.00%) and 3 metal EDs (50.00%); 1 buried at 5 cm (50.00%), 3 at 15 cm (100.00%) and 2 at 30 cm (33.33%; Table II).

IV. DISCUSSION

A. Effect of different GPR frequency antennas

Comparing the results obtained, when using a medium frequency (300 MHz) antenna and an antenna with lower frequency (100 MHz), it was clearly observed that for shallow subsurface investigation, higher frequencies allowed for better results than lower frequencies, due to the enhanced image resolution [15]. The same was stated by Metwaly et al. (2007) [16] when working with three different frequencies in a sandy soil (400, 900 and 1500 MHz), since it was seen that increasing the antenna frequency, the reflected signals resolution and amplitude were consequently increased, although the attenuation of the EM could also be enhanced. Also, in another study where two different frequency antennas (1 GHz and 2.3 GHz) were used to detect buried EDs, like mines, projectiles and mortars, at depths similar to those used in the present study, their results showed that the higher-frequency antenna allowed for better visualization of the reflection patterns [3]. However, in the present work, one of the smaller targets was detected with the antenna frequency of 100 MHz (instruction hand grenade Mod/962), which was not expected due to the low image resolution of the data normally obtained with this frequency.

The antenna frequencies, for landmine detection, used in previous studies were normally higher than the ones used in the present study with the 2D-Easyrad [3], [16], [17], [18]. As the targets were buried at shallow depths (maximum of 30 cm) and wave attenuation would not be a problem, the use of higher frequencies could have resulted in better detection due to the enhancement in resolution.

B. Effect of soil type and environmental conditions

As well as in the present study, previous field studies have shown that different soil and climatic conditions have an effect on GPR detection performance [19], [20].

Regarding soil type, the characteristics of the host material where an object is buried, have a huge effect on propagation of electromagnetic waves, playing a dominant role on GPR performance [19]. Soils with high content of clay particles, will consequently have high electrical conductivity, that affects the propagation of EM waves by attenuating them, thus limiting their propagation depth [6]. Literature suggests that GPR used in this soil type will produce poor data [21], [22], however in the present study, more inert explosive devices were detected in the clayey soil with the 300 MHz antenna, and thus not being in accordance with the predictions. As the targets were buried at shallow depths, attenuation of EM waves may not have affected so significantly the GPR detection performance when using the 300 MHz antenna. The soil is also not a pure clay soil since it has some siliciclastic components. On the other hand, with the 100 MHz antenna, lower percentages of detection were obtained in the clayey soil type, which is in accordance with the previous literature.

Relatively to the environmental conditions, an increase in soil water content will tend to enhance the host medium attenuation properties [15] that can result in poor detection of buried targets. In accordance, comparing the percentages of detection in the dry seasons (Spring and Summer) with the rainier seasons (Autumn and Winter), in the latter a decrease in GPR detection capability was seen in both soils for both of the used antennae. On the morning of the current Autumn survey day it rained, thus soils may had been saturated with water, explaining the lowest percentages of detection obtained. Miller et al. (2004) [23], when evaluating the effect of an increase in soil water content, verified that, despite decreasing the strength of landmine signature in a clayey soil, as seen in the obtained results, in a sandy soil the effect of moisture content enhancement was different depending on the landmine being metallic (poor detection) or non-metallic (better detection).

C. Effect of casing material (wood, plastic, and metal)

In very arid ground there are some measurements suggesting that plastic mines are more difficult to detect due to reduced dielectric contrast between the mine and the host soil, since dry sand and plastic objects have both low dielectric permittivity and conductivity [24]. However, an increase in sandy soil's water content allows for plastic mines to be readily detected [8], [23], since water leads to an enhancement in soil's electrical permittivity [6]. These data are in accordance with the obtained results with the 300MHz antenna, since inert explosive devices with plastic casing in the sandy soil were only detected at the Winter survey (Fig. 15), although only one could be noticed. Using the 100 MHz antenna in this soil type, also only one plastic explosive device was detected, although in the Spring survey (Fig. 15), which was not predictable.

At the clayey soil type, the explosive devices with plastic casing were much more easily detected using the 300 MHz antenna, with percentages of detection equal or exceeding 50.00% (Fig. 15), which is explained by the high contrast of EM properties, especially conductivity [6]. With the 100 MHz antenna, the explosive devices with plastic casing were not detected in this soil type (Table II). The metal explosive devices showed the higher average percentage of detection in the sandy and clayey soil for both antennas, which is due to the higher dielectric contrast [3]. Also, in a study published by Hara and Hirose (2004) [25] their results showed, that plastic mines are more difficult to detect than metal ones, even when using much higher frequency antennas.

Concerning the wood material, only one explosive device was used, the IED in a wooden box. This target, using the 300 MHz antenna, was detected at summer and winter surveys on the sandy soil and at spring and winter surveys on the clayey soil (Fig. 15), suggesting that neither the soil type nor environmental conditions have an effect on its detection. With the 100 MHz antenna this target was not detected (Table II). When using the 300 MHz antenna on the sandy soil, wood devices were more easily detected when compared to plastic devices, which did not happen on the clayey soil (Table II).

D. Effect of different targets burial depths

Concerning the different depths at which targets were buried, those buried at 5 cm below the ground surface were more difficult to be detect in both soil types while using the 300 MHz antenna, probably due to the strong interference caused by direct wave transmitted between both antennas and reflection from the ground surface [25], which can mask the target reflected signals (Table II). The targets buried at 30 cm below the surface, although easier detected than those buried at 5 cm, showed lower percentages of detection when compared to the targets buried at 15 cm, which can be explained by the fact that, increasing the burial depth, energy losses in the soil also increase, and only a smaller portion of the transmitted waves arrive at the landmine [26] (Table II). However, as it was used a medium frequency antenna (300 MHz), and the targets were buried at shallow depths, the effect of waves attenuation was not expected. Richardson and Cheetham (2013) also saw that, using a GPR with a 500 MHz antenna frequency to detect buried weapons, more strong signals were obtained when they were buried at 10 cm than at 30 cm or 50 cm [27].

When using the 100 MHz antenna, different results were obtained for the sandy and clayey soil. In the sandy soil, although better average percentage of detection was obtained for the targets buried at 15 cm, similar to the results obtained with the 300 MHz antenna, the average percentage of detection of the targets buried at 5cm were higher than that for the ones buried at 30cm. This was not expected since lower frequency antennas can accomplish higher penetration depths of EM waves [28], being likely an easier detection of targets buried at greater depths. At the clayey soil type, the only target detected was at 30 cm.

V. CONCLUSION

In the present field study, it was demonstrated that the capacity of 2D GPR detection, of inert explosive devices, can be affected by all the tested variables, namely: antenna frequencies, environmental conditions, soil types, targets casing material and burial depths. According to the obtained results, optimal GPR performance can be achieved when using higher frequency antennas. Through the use of the 300 MHz antenna, the best detection capacity was achieved under good environmental conditions (Summer and Spring), in the clayey soil type and on metal targets and targets buried at depths of 15 cm. When using the 100 MHz antenna, results were similar, however the latter presented better results in the sandy soil and when used in the clayey soil, the best detection performance was at depths of 30 cm. Even with a better 100 MHz antenna performance in these two referred specific conditions, the use of the 300 MHz antenna seems to be always more suitable to detect inert explosive devices buried at shallow depths, since the percentages of detection were always higher, independently of the condition being tested.

In future, it is important to perform blind studies, without comparing the known position of the buried targets with the GPR signals, in order to simulate more closely what happens in real demining situations, thus decreasing possible bias in the interpretation of the results.

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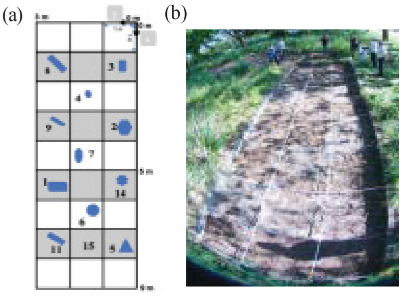


Fig. 1. Sandy soil study site, in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, Porto: (a) schematic representation of targets' distribution and (b) aerial image (meaning of numbers present in Table I).

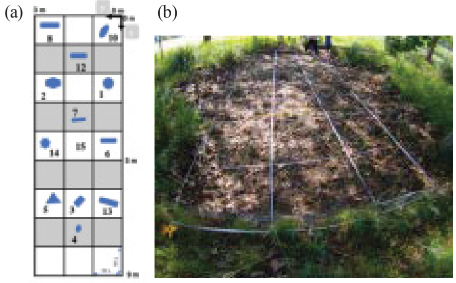


Fig. 2. Clayey soil study site, in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, Porto: (a) schematic representation of targets' distribution and (b) aerial image (meaning of numbers present in Table I).

Table I. Inert explosive devices and controls, buried in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia (Porto, Portugal), their casing materials and burial depths.

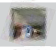
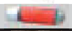
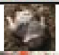
Buried targets	Photographs	Casing Material	Depth (cm)
(1) Antipersonnel mine		Plastic	15
(2) IED (improvised explosive device)		Plastic	30
(3) IED (improvised explosive device)		Wood	30
(4) Instruction hand grenade Mod/962		Plastic	5
(5) MILLS hand grenade		Metal	5
(6) Rocket grenade		Metal	15
(7) 81mm mortar grenade		Metal	15
(8) 155mm artillery projectile		Metal	30
(9) 80mm artillery projectile		Metal	30
(10) 60mm artillery projectile		Metal	30
(11) 101mm artillery case		Metal	30
(12) 105mm artillery case – Blank M365 cartridge case		Metal	30
(13) Firend		Plastic	30
(14) Organic control		(Chicken)	30
(15) Negative control		(Empty hole)	30

Fig. 3. 2D-Easyrad.GPR system.

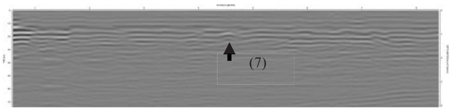


Fig. 4. 300 MHz antenna radargram, obtained in the Spring season, at 1.2 m of the y axis of the sandy soil type, with indication of a signal that could correspond to the 81 mm mortar grenade (7), buried between 4 to 5 m of the X axis.

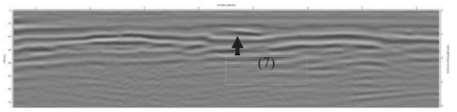


Fig. 5. 100 MHz antenna radargram, obtained in the Spring season, at 1.2 m of the y axis of the sandy soil type, with indication of a signal that could correspond to the 81 mm mortar grenade (7), buried between 4 to 5 m of the X axis.

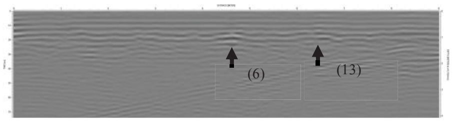


Fig. 6. 300 MHz antenna radargram, obtained in the Spring season, at 0.2 m of the y axis of the clayey soil type, with indication of signals that could correspond to the rocket grenade (6), buried between 4 to 5 m of the X axis and to the firend (13), buried between 6 to 7 m of the X axis.

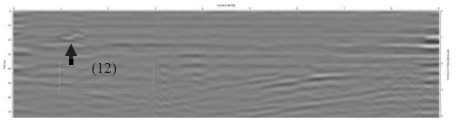


Fig. 7. 100 MHz antenna radargram, obtained in the Spring season, at 1.2 m of the y axis of the clayey soil type, with indication of a signal that could correspond to the 105 mm artillery case (12), buried between 1 to 2 m of the X axis.

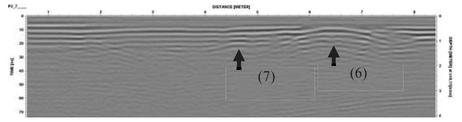


Fig. 8. 300 MHz antenna radargram, obtained in the Summer season, at 1.4 m of the y axis of the sandy soil type, with indication of signals that could correspond to the 81 mm mortar grenade (7), buried between 4 to 5 m of the X axis and to the rocket grenade (6), buried between 6 to 7 m of the X axis.

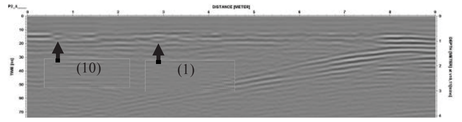


Fig. 9. 300 MHz antenna radargram, obtained in the Summer season, at 0.8 m of the y axis of the clayey soil type, with indication of signals that could correspond to the 60 mm artillery projectile (10), buried between 0 to 1 m of the X axis and to the antipersonnel mine (1), buried between 2 to 3 m of the X axis.

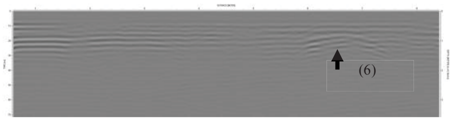


Fig. 10. 300 MHz antenna radargram, obtained in the Autumn season, at 1.8 m of the y axis of the sandy soil type, with indication of a signal that could correspond to the rocket grenade (6), buried between 6 to 7 m of the X axis.

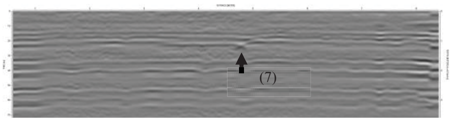


Fig. 11. 100 MHz antenna radargram, obtained in the Autumn season, at 1.6 m of the y axis of the sandy soil type, with indication of a signal that could correspond to the 81 mm mortar grenade (7), buried between 4 to 5 m of the X axis.

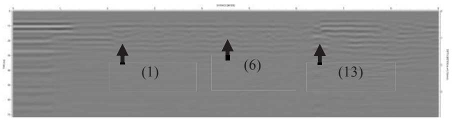


Fig. 12. 300 MHz antenna radargram, obtained in the Autumn season, at 0.6 m of the y axis of the clayey soil type, with indication of signals that could correspond to the antipersonnel mine (1), buried between 2 to 3 m of the X axis; to the rocket grenade (6), buried between 4 to 5 m of the X axis and to the firend (13), buried between 6 to 7 m of the X axis.

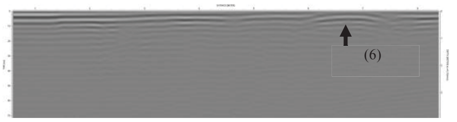


Fig. 13. 300 MHz antenna radargram, obtained in the Winter season, at 1.2 m of the y axis of the sandy soil type, with indication of a signal that could correspond to the rocket grenade (6), buried between 6 to 7 m of the X axis.

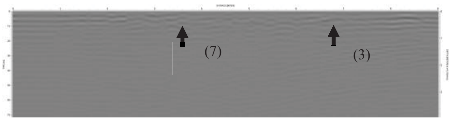


Fig. 14. 300 MHz antenna radargram, obtained in the Winter season, at 1.8 m of the y axis of the clayey soil type, with indication of signals that could correspond to the 81 mm mortar grenade (7), buried between 3 to 4 m of the X axis and to the IED in a wooden box (3), buried between 6 to 7 m of the X axis.

Table II. Percentages of inert explosive devices detection, obtained using a 2D-Easyrad on sandy (1)) and clayey soil (2)), at the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia (Porto, Portugal): a) average in each frequency antenna considering only Spring and Autumn; b) in each season; c) average in each soil type; d) average in different casing materials and e) burial depths with the results (- scans not performed; *n=1; $^{\#}$n=2; $^{+}$n=4).

		1) Sandy soil		**2) Clayey soil**	
		100MHz	300MHz	100MHz	300MHz
a) Antenna frequency (average)		$^{\#}$20.00%	$^{\#}$40.00%	$^{\#}$4.50%	$^{\#}$54.50%
b) Environmental conditions	Spring	*30.00%	*60.00%	*9.00%	*64.00%
	Summer	-	*60.00%	-	*64.00%
	Autumn	*10.00%	*20.00%	*0.00%	*45.00%
	Winter	-	*50.00%	-	*54.00%
c) Soil type (average)		$^{\#}$20.00%	$^{+}$47.50%	$^{\#}$4.50%	$^{+}$56.75%
d) Type of casing material (average)	Wood	$^{\#}$0.00%	$^{+}$50.00%	$^{\#}$0.00%	$^{+}$50.00%
	Plastic	$^{\#}$16.67%	$^{+}$8.33%	$^{\#}$0.00%	$^{+}$56.25%
	Metal	$^{\#}$25.17%	$^{+}$66.67%	$^{\#}$8.50%	$^{+}$58.33%
e) Depth of burial (average)	5 cm	$^{\#}$25.00%	$^{+}$37.50%	$^{\#}$0.00%	$^{+}$25.00%
	15 cm	$^{\#}$33.33%	$^{+}$58.33%	$^{\#}$0.00%	$^{+}$91.67%
	30 cm	$^{\#}$10.00%	$^{+}$45.00%	$^{\#}$8.50%	$^{+}$50.00%

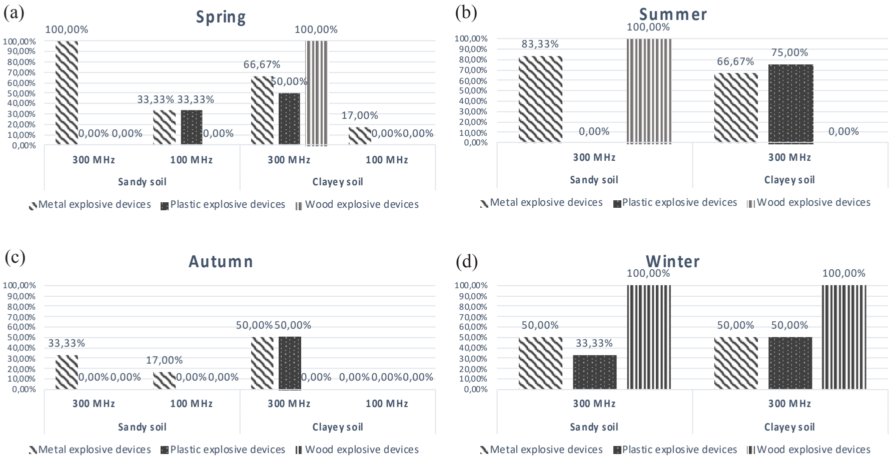


Fig. 15. Graphic representations of the percentages of inert explosive devices detection towards the different casing materials (metal, plastic and wood) on sandy and clayey soil at the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia (Porto, Portugal), using the 2D-Easyrad with the 300 MHz and 100 MHz antennas in: (a) Spring; (b) Summer; (c) Autumn; and (d) Winter.

Attachment 2. Review article submitted to Forensic Science International.

Forensic Science International

Ground Penetrating Radar for Buried Explosive Devices Detection: A Case Studies Review

--Manuscript Draft--

Manuscript Number:	
Article Type:	Review Article
Keywords:	GPR; geophysics; UXOs; IEDs; soil
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Abstract:	Geophysical techniques can be successfully applied towards detection of buried explosive devices, the ground penetrating radar (GPR) being an example of one of those. This technology works through emission and reception of electromagnetic waves being able to detect the presence of a subsurface object due to contrasting electromagnetic properties between the object and the surrounding medium (e.g. soil). Many factors can affect the success of a GPR survey (e.g. target type, soil type, environmental conditions, GPR antenna frequency, data processing techniques), being important to previously know their likely effects prior to the performance of GPR studies, mainly in real cases. In this paper, through the analysis of case studies related to the use of GPR technology towards the detection of buried explosive devices, we intend to arrange and lay out the prior knowledge that a forensic geophysical expert must have when dealing with this type of field work.
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Opposed Reviewers:	

Title Page (with authors and addresses)

Ground Penetrating Radar for Buried Explosive Devices Detection: A Case Studies Review

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Declaration of interests: none.

Abstract

Geophysical techniques can be successfully applied towards detection of buried explosive devices, the ground penetrating radar (GPR) being an example of one of those. This technology works through emission and reception of electromagnetic waves being able to detect the presence of a subsurface object due to contrasting electromagnetic properties between the object and the surrounding medium (e.g. soil). Many factors can affect the success of a GPR survey (e.g. target type, soil type, environmental conditions, GPR antenna frequency, data processing techniques), being important to previously know their likely effects prior to the performance of GPR studies, mainly in real cases. In this paper, through the analysis of case studies related to the use of GPR technology towards the detection of buried explosive devices, we intend to arrange and lay out the prior knowledge that a forensic geophysical expert must have when dealing with this type of field work.

Keywords: GPR; geophysics; UXOs; IEDs; soil

1. Introduction

Even at the moment, with the treaties of non-proliferation and non-use of landmines and other kind of explosive weapons, more than 70 countries are estimated to have between 80 and 110 Million of buried explosives, which kill or cripple an average of 70 people per day [1], making this subject a safety problem that affects millions of people around the world [2,3]. Some characteristics, pointed in the United Nations Mine Action Service (UNMAS) Safety Handbook [4], summarize target issues of this threat, namely their negative effects even years after the end of a conflict and the difficulty to find them since they are usually hidden in grass, buildings, vehicles or even buried under ground or water, being the affected areas mostly not flagged. Therefore, the possibility of detection and also identification of this ordnance (e.g. mines, improvised explosive devices (IEDs), unexploded ordnance (UXOs)) is needed, in order to allow for a secure removal [5].

Ground Penetrating Radar (GPR) is a geophysical, non-invasive method, recognized by the scientific community for mine and UXOs detection [6,7] that uses the reflection of electromagnetic (EM) radio waves to detect discontinuities on the subsurface, thus allowing to find targets without surface disruption and ground excavation [8]. The GPR technology was first used by Stern, to determine a glacier depth in 1929, being widely used in a range of applications since the beginning of the 1970's [9].

The commercial GPR systems have a transmitting and receiving antenna, a control unit, a laptop to control and storage data, and a power supply (battery). The antennas can be in direct contact with the ground surface or close to it (easier scanning process). The transmitting antenna generates an electromagnetic pulse into the ground, that is reflected when encountering discontinuities on the subsurface (*e.g.* a soil/bedrock interface, a boundary between different soil types, some underground structures or buried objects. The electromagnetic radio energy reflected back to the surface is captured by the receiving antenna and recorded allowing for the formation of a high-resolution reflective image of shallow subsurface features [10]. The EM radio waves that do not reflect, simply continue to deeper subsurface levels [8] and may eventually be reflected back from existing layers with sufficient impedance. A GPR system can work in two different domains: time and frequency. When operating in the time-domain it transmits a succession of EM radio pulses that occupy a frequency band from several Megahertz (MHz) up to several Gigahertz (GHz) [11], and process the received signal using an analog to digital converter (ADC) thus sampling the time domain signal. When operating in the frequency domain it transmits individual frequencies in a sequential manner or as a swept range of frequencies and receive the reflected signal using a frequency conversion receiver [12]. When GPR scans are made perpendicular to the ground surface, one-dimensional signals are obtained, being called A-scans. However, the GPR system can be moved along a straight line horizontal to the surface of the ground, originating adjacent A-scans that form a two-dimensional image, B-scan [13].

The GPR systems read the contrast of two important electrical properties of the soil and features within it, in order to detect discontinuities, the dielectric permittivity (ε) and the conductivity (σ). The higher the contrast of these properties between two materials, the stronger the reflected signal in the GPR profile [14]. These two properties are greatly influenced by the water content of the soil, since it will increase both dielectric permittivity and conductivity, so, due to that, moisture has a huge influence on GPR performance [10]. Conductivity is also influenced by the presence of clay minerals, which lead to an increase in this property [8]. In its turn, the conductivity influences the rate at which the energy is absorbed [10]. Therefore, in more conductive soils, the GPR will have a poor performance since the energy penetrating the soil will be attenuated at a high rate. The performance of the GPR depends also on other several parameters related with the soil surface (e.g. texture, density) and also on the operating frequency [13]. The used antenna frequency is directly linked to the performance of the GPR system. Normally, high frequencies allow for a better image resolution of the subsoil but are very attenuated, not allowing for a good depth penetration. On the other hand, low frequencies have deeper penetrations but present lower image resolution. The frequency of the antennas must be carefully chosen, for any specific application, being necessary to achieve a compromise between resolution and the depth of interest [10].

The raw data obtained with the GPR method can be easily verified on the acquisition console or computer screen in real time, however, a lot of times, depending on the application and targets of interest, it is necessary to process this data using more sophisticated routines found in GPR processing software [10] for easier and clearer visualization and more accurate interpretation [8]. Like all methods, GPR also has limitations, MacDougall *et al.* [15] pointed out a few: the presence of buildings, contructed structures or anthropogenic metallic objects at ground surface (e.g. overhead power cables, vehicles, gates) can interfere with target results; the existence of access problems to the zone of interest (e.g. vegetation, animals, agriculture); the existence of electrical interference (e.g. mobile phones, power cables)"; issues related to "severe ground topography" and "seasonal factors (e.g. tourists, weather)". Daniels *et al.* [16] also referred the presence of buried non-target objects (e.g. cables, pipes, reinforced concrete) as a limitation that may produce false positive results.

2. Applications

Being able to efficiently map the subsurface of the earth in a non-destructive manner, GPR systems have been operated in a range of field works, ranging from civilian to military [17]. It has a major role in civil engineering, in utility mapping (detection of pipes, cables, voids), road/concrete inspection (asphalt thickness, base layer profiling, location of instabilities, deformations, damages); in environmental applications including studies of ground contamination by hazardous waste disposal, plumes of contaminated groundwater and investigations of underground storage tanks; in studies of geology and geophysics, like stratigraphy, bedrock profiling, determination of soil water content and conductivity, agriculture and forestry (golf course maintenance, tree assessment), mining (mine safety, mineral exploration), and in ice and snow (ice road thickness, glaciology studies); in archaeological investigations (optimize excavations, locate and map artefacts, graves and historic sites); in search and rescue operations (locate victims trapped under collapsed buildings and landslides); in detection of clandestine bunkers or tunnels; in localization of clandestine burials of forensic evidence, objects or bodies and in law enforcement and military applications, which include detection of buried explosives/weapons and in the detection of landmines and buried unexploded ordnance (UXO).

3. Case studies

3.1. Evaluation of the performance of mines and UXO detection with GPR technology: effect of soil properties

In 1994, at the Jefferson Proving Ground (JPG), located 5 miles north of Madison, Indiana, the capacity of different technologies on the detection and identification of UXO was tested , in two controlled sites, being the GPR one of the tested systems. Inert ordnance and other nonordnance items were emplaced on each site, where the capacity of detection of hand-carried, airborne and remediation systems were demonstrated. The performance of the systems was evaluated by their detection capability and false alarm rate, which were obtained with the utilization of a software called Target Matching Algorithm (TMA).

The capacity GPR to detect mines and distinguish them from clutter (stones) were tested. The results for high frequencies between 1 to 3 GHz, showed that a mine with 114 mm buried at 12 cm, gave a similar response comparing to a 76 mm stone buried at 6 cm and a 51 mm stone just under the surface, giving a lower response when compared to a 76 mm stone displayed on the surface. It was concluded that mines couldn't be discriminated with the GPR systems due to the high ground conductivity and water content of the soil, that rapidly attenuate the high frequencies, being those necessary for the detection of small size mines. A homogeneous and dry soil would be the only way to obtain a high probability of detection and low false alarms.

The capacity of detecting projectiles was also studied, with the utilization of a 155 mm artillery shell, buried horizontally at a depth of 0,5 m and the use of GPR operating at low frequencies, below 500 MHz. The response to the shell, when compared to the response to a 20 cm flat rock near the surface was weaker or equal. Artillery shells are large enough to be detected with low frequencies, which are less attenuated. However, at JPG, since the conductivity is very high and the shell were buried too deep, the low frequencies were also attenuated and could not reliably detect and discriminate the shell from the background objects.

The poor performance of the GPR in the detection and discrimination of the UXOs and clutter could be partial explained by the high moisture content and high ground conductivity at the JPG site [18].

3.2. Application of algorithms for feature extraction to GPR signals for landmine classification

A comparison of two methods for feature extraction from the GPR signals (the Wigner-Ville distribution (WVD) and the Wavelet Transform (WT)) was performed. The aim was to see which one could be more useful for landmine classification. The used GPR system was the MINEHOUND, consisting of a pulse induction metal detector (MD) VHMD3.1 from VALLON and an ERA GPR. Scans were made on two different scenarios, one sand lane and one ballast lane. In both scenarios, different types of antipersonnel (AP) landmines (different shapes) and different clutter targets (a stone and a metallic can) were buried, at different depths.

The feature extraction methodology was applied to the appropriate A-scans selected from the pre-processing B-scans obtained. Results from the WVD showed that this method has a good performance when differentiating AP landmines from clutter targets, when differentiating between clutter targets, and when distinguishing different mine types (different shapes) and the same mine type buried at different depths. To compare the performance of the WVD and the WT, the Wilk's lambda value was used, showing how well the methods could separate different target classes (mines from clutter). The WVD showed a good discrimination of all type of AP landmines, while the WT only discriminate the AP landmines with regular shapes (cylindrical and rectangular).

From the results obtained it was concluded that the WVD allows for better discrimination of the AP landmines [19].

3.3. Evaluation of GPR performance towards metallic and plastic landmines detection

Landmines in Egypt started to be a problem in the II World War, in the northern part of western desert. This study focuses on the understanding of the GPR performance when trying to detect ten landmine-like objects, buried at different depths, in a sandy soil similar to the one of the Western Desert of Egypt. The test-site dimensions were 2.5m×6.0m and different materials (metallic, low metallic and non-metallic (plastic)) were buried. The large metallic objects resemble to a metallic anti-tank (AT) mine (T-80), while the majority of the plastic ones are similar to antipersonnel (AP) mine (Ts-50). Since it has been described some limitations of the GPR technique in the detection of low and non-metallic landmines, electrical resistivity imaging (ERI) was tested. GPR surveys were made using SIR 20 system (from GSSI), operating with a 400, 900 and 1500 MHz antenna frequency, being the obtained data processed with REFLEX software having applied the background removal and the band pass filter.

With the increase of the antenna frequency, the resolution of the obtained signal also increased, which allows the visualization of some object details. Furthermore, the dimensions of the smooth reflected hyperbole of two metallic AP mine-like objects was comparable to their diameter; there were interferences on the reflected signals of a metallic AT mine-like and a UXO-like object; and low and non-metallic targets signals were weak and difficult to be detected, probably due to their low dielectric constant, in contrast with the host soil. The reflected signals of the nonmetallic objects were improved by increasing the applied frequency, however, this increase attenuated the radar wave propagation.

It was observed that the detection of metallic targets using GPR technique were very easy since they create a high reflected signal, due to the high contrast in conductivity of the metallic mines and the relatively high dielectric contrast with the surrounding medium. For the same reason the detection of low and non-metallic landmines can only have success if there is a high contrast of the electrical properties. As alternative to detect low metallic and totally plastic landmines buried in conductive environment, the geophysical method ERI proved to be useful [2].

3.4. Development of a discriminator algorithm for landmine classification

The performance of a GPR system to discriminate and classify anti-personnel (AP) landmines was demonstrated. The used system was the MINEHOUND^{TM} – VMR2, consisting of a GPR developed by ERA Technology Ltd (UK), which is an ultra-wideband time radar, and an induction Metal Detector based on the VMH3 manufactured by Vallon GmbH (FRG). In this study, inert AP landmines were used: VS50, Type 72, R2M2, PMA2 and PMA3. A stone, a piece of wood, a coke can and a pipe were also buried to test the capacity of discrimination between clutter targets and the inert landmines.

The main aim was to test methods that can be capable of correctly classify landmines and clutter targets. The two first discriminator algorithms employed were the RMS (Root-Mean-Squared) error and the Pearson’s Correlation Coefficient, being applied to the A-scans from the GPR datasets. The results revealed that the RMS A-scan error have an enhanced capacity of discrimination, not showing any false result. The other tested method was the RMS complex FFT (Fast Fourier Transform) error. When combining this method in a variety of ways, the best discrimination was obtained combining the RMS A-scan error with the RMS complex FFT error. This combination was evaluated on a blind test, with new data being collected two weeks later with the same GPR system, in the same ground and buried targets. The results showed an optimal discrimination of each target type against other targets and clutter, producing no false negative results, with the exception of the pipe that caused some false positive results [16].

3.5. GPR detection of buried forensic objects in a semi-urban and domestic patio environment

A set of current commercial geophysical equipment to locate several buried metallic objects was used. The surveys where both made in a semi urban environment (representative of a U.K. garden) and in the same terrain after a placement of 6 cm concrete slab patio (representative of a common domestic property garden). The study aimed to compare the remaining techniques with GPR detection method; to determine optimum GPR detection frequencies and the optimum respective equipment configurations/ survey specifications/ processing steps; to determine which technique(s) could establish the target depth below ground and to determine if different buried metal types could be distinguished.

The test site (5mx5m) was located on Keele University campus near Stoke-on-Trent, in England, U.K. A set of 8 forensic, mostly metallic, targets (bread knives, spade, knife, WWII (World War II) grenade, WWI (World War I) grenade, handgun, mortar shell and ammunition box) and 3 non-forensic targets (a brick, a metallic bolt and a steel plate) where buried at 15 cm, in a non-ordered configuration being their locations recorded.

GPR surveys were made using pulseEKKO™ 1000 equipment with a 450 MHz and 900 MHz dominant frequency bi-static, fixed-offset (0.34 and 0.17 m respectively) antennae, along 0.25 m spaced lines and having trace sample intervals of 0.05 m and 0.025 m respectively, being then processed using Reflex-Win™ Version 3.0 (Sandmeier) software using the following steps: 1) 'Dewow' (low-cut filter); 2) Move to constant start-time; 3) 1D bandpass filter (Butterworth; 4) 2D filter; 5) Stolt migration and 6) horizontal time-slice generation of each dataset.

The rate of detection on the semi-urban environment was 50 % using 450 MHz and 75 % using 900 MHz and in the patio environment the result was 63 % using 450 MHz and also 75% using 900 MHz, having a higher rate than the magnetic methods. These rates showed that the 900 MHz is the best GPR detection frequency. Another important result was that only GPR data could determine the depth of the target below ground level. The optimum survey conditions suggested to be the 0.025 m trace sampling interval on 0.25 m spaced survey lines. Despite the important conclusions, concerns about the detection with GPR were raised since some important targets like knives and hand grenades were not detected even with the 900 MHz frequency, especially in the patio environment [20].

3.6. Feasibility of GPR technology towards the detection of buried weapons caches and UXOs

Experiments to understand the effectiveness and feasibility of GPR to detect buried weapons and UXO, knowing the depth, size, and dimensions of the targets, were performed. Little iron, plastic and wooden boxes filled with iron and copper materials plus empty plastic boxes were put inside a bigger wooden box and then buried with sand at the depth of 25 cm. The equipment used to collect GPR data was SIR-3000 Geophysical Survey System Inc. (GSSI) with a 1.5 GHz central frequency monostatic antenna. Two surveys were performed for each buried box with two antenna polarizations (i.e. one perpendicular to the box sand long axis and the second one being parallel) to be able to understand how the configuration would affect the direction in relation to the antenna radiation pattern. GPR data were post-processed with RADAN 7 GSSI software, having applied zero-time process, background removal and Hilbert Transform.

A change or contrast in the electromagnetic impedance is what causes reflection. A higher impedance target yields a positive reflection coefficient, however a negative reflection coefficient is due to a lower impedance. Concerning GPR results, metal is a low impedance material which can be translated to a negative reflection wavelet, whereas an empty box is a high impedance material and can be translated to a positive reflection wavelet. Therefore, filled iron, plastic and wooden box showed a negative reflection wavelet and the empty plastic box a positive reflection wavelet. The dielectric constant of sand was measured, and the investigators could calculate the depth and dimensions of the target in the field (using a specific formula). Due to this study, it is now possible to predict the material type, depth and the dimensions of certain targets [8].

3.7. Application of machine learning algorithms to GPR data for automatic detection and classification of UXOs and landmines

In this study, the capacity of a commercial GPR system in the detection of buried UXOs was evaluated and it was also created and applied a real-time mine detection procedure. The test site was a sandy soil of the Spanish Naval Academy in Marín, Galicia (Northern Spain). Different landmine types, grenades and other non-explosive materials (like stones, plastic bottles and wooden planks) were buried at different depths and orientations, simulating a real minefield scenario. The frequencies chosen to test the GPR system were 1 and 2.3 GHz and to test the capacity to automatically detect and classify UXOs, two machine learning algorithms were used, the logistic regressions and neural networks.

The used GPR was the ProEx Control Unit from the MALA Geosciences, a modular digital radar with multi-channel functionality and the software used to process GPR data was the ReflexW v.5.6, filtering with the time-zero correction, dewow filtering, gain function and subtracting average, consecutively applied. The buried explosives included two types of plastic landmines (AP-SB33 anti-personnel (AP) mines and the AT-SB81 anti-tank (AT) mines), several metal mortar grenades (INSTALAZA II-M63 and GM-ECIA, with and without the fuse) to simulate UXOs, and two types of hand grenades (M-67 (metal) and ALHAMBRA-EJ (plastic)). In addition, non-explosive items were also buried to compare their signals on GPR with the ones of the explosives, and also to train the automatic mine detection application to distinguish the mines from clutter. For each target type and buried orientation, radargrams with the two frequencies were produced. Analyzing the responses to the AP mines, the one buried vertically was only identified with the 2.3GHz antenna and the ones buried horizontally and obliquely were identified with the two frequencies. The AT mine buried horizontally had the same results as the horizontal AP mine, and the vertical and oblique AT mines the same responses as the oblique AP mine. The oblique and horizontal GM-ECIA mortar grenades were distinguished with continuous flat reflections when using both frequencies. The different lengths of the grenades, with and without the fuse, where also observed in the radargrams. Similar responses were given by the INSTALAZA II M-63 mortar grenade buried horizontally. The oblique M-63 mortar grenades, with and without the fuse, with the 2.3GHz antenna, presented a half-hyperbolic reflection and, with the 1GHz antenna, a continuous reflection. The hand grenades, the M-67 buried horizontally, and the vertical and horizontal ALHAMBRA-

E3, exhibited a hyperbolic reflection, while the oblique ALHAMBRA-EJ showed a half-hyperbolic reflection with the 2.3GHz antenna, being not clearly detected with the 1GHz antenna.

It was observed that the metal objects, like the mortar grenades and the M-67 hand grenade, presented the greater reflections, but the plastic objects, like the landmines and the ALHAMBRA-EJ hand grenade, were also clearly detected. Both frequency antennas provided good results, however the 2.3 GHz antenna proved to be ideal for detecting shallow AP mines (10 cm depth), while for the deeper AT mines (25 cm and 30 cm depth) the detection was best achieved with the 1GHz antenna.

The proposed learning technique consisted on feeding the GPR interpretation system with data, making it capable to learn and distinguish the characteristic patterns of the background noise from those of the desire targets, providing the probability of a buried explosive device being in a certain area. In order to show the capacity of the logistic regression and neural network to automatically detect the presence of buried explosives, GPR radargrams showing where the targets were buried were compared with the radargrams after the application of the technique. It was shown that, when the reflection is clear, the logistic regression correctly identifies the real position of the mines, however, when the signal becomes indistinct, only the neural network remains accurate. The two learning algorithms were compared taking into account the accuracy and the error rates. For detection and differentiation between targets and clutter, the neural network provides better results, showing the highest probability of detection and the lowest probability of false positive and negative results, especially when using radargrams obtained with the 2.3 GHz antenna [3].

3.8. Development of a recognition technique for GPR improvised explosive devices (IEDs) detection

A developed recognition technique, using the GPR for counter IEDs in Thailand was presented. Data were collected with a commercial GPR system and the proposed technique, called region analysis processing, was applied to the obtained B-scan images, where the buried object is presented as a hyperbolic curve. The technique includes 4 steps: ground surface elimination, normalization, elimination of background and region analysis (that comprises regionalization and hyperbolic identification).

The GPR scans were made on two experimental setups, in an anechoic chamber and in a real road, being the used target a 32x67cm gas tank that simulates an IED. B-scan images of the IED were obtained with the GPR, being then processed with the proposed technique. Afterwards, from the processed B-scan images, the appropriate A-scan signal was selected from the center of the image. A method called short-time matrix pencil was applied to the A-scan signal allowing the extraction of the resonance frequency, in order to demonstrate the target identification.

It was concluded that the use of the region analysis processing on B-scan images is efficient for detection of the hyperbolic curve that represents the target. For the identification of the IED, the extraction of the resonance frequency from the A-scan signal also proved to be efficient [21].

3.9. Evaluation of the effect of soil and climatic conditions on the performance of GPR

The effect that different soil conditions can have on GPR, when used for detection of buried objects was shown in four test sites (Australia) of different geographical regions and climatic conditions (one arid and three temperate). At each site, two soil properties were measured, the magnetic susceptibility and dielectric permittivity. The magnetic susceptibility was different for every site and very variable within each site, while the dielectric permittivity showed clearly local variation and separation between the arid and the temperate sites.

To test the influence of the soil conditions, GPR signatures of chosen targets were obtained using a vehicle-mounted 3D-RADAR array, with a Stepped Frequency Continuous Wave (SFCW) transmit waveform. The scanning was made over a continuous 200 MHz to 3 GHz frequency range. GPR signatures of an anti-tank mine in all four test sites were shown, where is possible to observe a slightly weaker signal at the arid region in comparison to the three temperate regions. These results confirm that different geographical regions and climatic conditions have an effect on GPR signatures of buried explosive devices [11].

4. Conclusions

The possibility to detect buried explosive devices is of major urgency, being an important matter in a great number of countries, mainly in those who have passed through an armed conflict. GPR systems have shown good performances in order to fulfil this need, since even with some limitations, the systems actually allow to predict important information (burial depth, dimensions, material types) about the targets. In order to detect buried explosive devices, the GPR antenna frequency must be carefully chosen taking into account the size, shape and material of the possible existent targets and their possible buried depths, considering also the soil properties. The use of an antenna frequency that is not adequate to a specific context will affect greatly the performance of the system and it’s ability to detect certain objects. Moreover, the chosen algorithms for processing GPR raw data are also important in achieving an effective detection and discrimination of targets from clutter, by transforming signals into meaningful information. The development and use of machine learning techniques and discriminator algorithms to automatically detect and discriminate explosive devices is useful in order to obtain a more rapid, easier and accurate detection, reducing false results.

A good performance of the GPR systems can be confirmed in the presented case studies, however, more trials in different conditions and using different variables should be considered to hereafter develop certified protocols, suitable to specific soil types, in order to be implemented by police and military forces in real cases, involving the detection of underground explosive devices.

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USE OF A 3D GROUND-PENETRATING RADAR FOR DETECTION OF BURIED INERT EXPLOSIVE DEVICES

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ABSTRACT

A dangerous problem that many countries have to face is the existence of buried explosive devices, responsible for high numbers of civilian fatalities. Their detection and removal are therefore mandatory, which has led in recent years to the development of different techniques that can ensure safer and more efficient demining operations. Geophysical techniques have been employed, since allow ground search in a non-invasive, rapid and cost-effective way, with special interest being given to ground penetrating radar (GPR). In the current work, it was buried in a sandy soil and in a clayey soil (27m^2 each), one of two similar sets of different inert explosive devices. GPR profiles of the subsoil were obtained with a 3D-GPR system, being then processed with the ReflexW software. Three dimensional cubes of the two study sites were constructed for better target signal visualization. The preliminary results confirm the efficiency of this technique, since all buried inert explosive devices were detected in both soil types.

Keywords: Forensic geophysics; GPR; Safety; IED; UXO;

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1. INTRODUCTION

Detection and removal of buried explosive devices is fundamental, with nearly 70 countries being affected with this problem that has resulted in the injurie and death, not only of military personnel, but also civilians. These explosive devices can be found in a huge variety of environmental conditions, from desert regions and mountains, to urban areas, at various depths and distributions [1], which contributes to the challenging work of finding techniques that could effectively work in all of these diverse conditions.

Ground penetrating radar (GPR) is now an established geophysical technique, that has been successfully employed in the detection of buried landmines and unexploded ordnance (UXO) [2]. This technology works through emission of electromagnetic (EM) waves, of frequencies varying from a few MHz up to 1000 MHz, that are reflected back to the surface, and consequently detected by a GPR device, due to contrasting EM properties between the surrounding medium and the targets [3].

Contrary to the techniques commonly used in demining operations, like excavations, metal detectors and biological detectors (e.g. dogs, pigs, rats), which although efficient, show a lot of drawbacks, like slow, invasive and dangerous demining processes , GPR contributes to a more rapid, safer and non-invasive way of subsurface exploration and detection of these hazards. Furthermore, it has been successfully used in a wide range of soils and environmental conditions and can detect both metal and plastic explosive devices [4], [6].

In this study, a 3D GPR system, from 3D-Radar, was used to detect different types of buried explosive devices, with metal, plastic or wood casing material, being buried at different depths, in two different soil types, a sandy and a clayey soil. The main aim of this study was to analyze the capacity of this GPR system in the detection of buried inert explosive devices in relation to three variables: soil type, explosive casing material and burial depth.

2. MATERIAL AND METHODS

The present study was performed in the Winter season, inside a facility of the Military Unit of Serra do Pilar, a former Artillery Regiment Unit (41°14'N, 08°60'W), located in the city of Vila Nova de Gaia, Porto, 400 meters south of the Douro river.

Two study sites of 3mx9m (27m^2 each) of two different soil types (sandy and clayey) were selected and then being buried 10 inert explosive devices in the sandy soil and 11 in the clayey soil, plus an organic control (chicken) and a negative control (empty hole), in each soil. These inert explosive devices were loaned by the *GNR - Destacamento de Intervenção do Porto* and included two improvised explosive devices (IEDs), one antipersonnel (AP) landmine, two hand grenades and examples of UXOs (rockets, mortars and artillery ammunition). Table 1 presents the identification of each used target, with reference to the explosive device casing material and the depth of burial. Figures 1 and 2 present the burial target distribution in the sandy and clayey soil, respectively.

The GPR scans were performed with the 3D-Radar (Figure 3), being parallel to the 9-meter side of each study site. This GPR system includes some innovation in the form of a step-frequency data collection technique. The GeoScope is coupled to a distinctive multi-channel antenna array, of 1.8 meterwide, containing 23 pairs of antennas. It also has a wide frequency range, between 100MHz-3GHz, allowing optimization towards different study objectives.

Table 1. 3D-GPR targets buried in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, Porto.

Buried targets	Casing Material	Burial Depth (cm)
(1) Antipersonnel mine	Plastic	15
(2) IED in a plastic box	Plastic	30
(3) IED in a wooden box	Wood	30
(4) Hand grenade Mod/962	Plastic	5
(5) MILS hand grenade	Metal	5
(6) Rocket grenade	Metal	15
(7) 81mm Mortar grenade	Metal	15
(8) 155mm Artillery projectile	Metal	30
(9) 80mm Artillery projectile	Metal	30
(10) 60mm Artillery projectile	Metal	30
(11) 101mm Artillery case	Metal	30
(12) 105mm Artillery case	Metal	30
(13) FIREND	Plastic	30
(14) Negative control		30
(15) Organic control		30

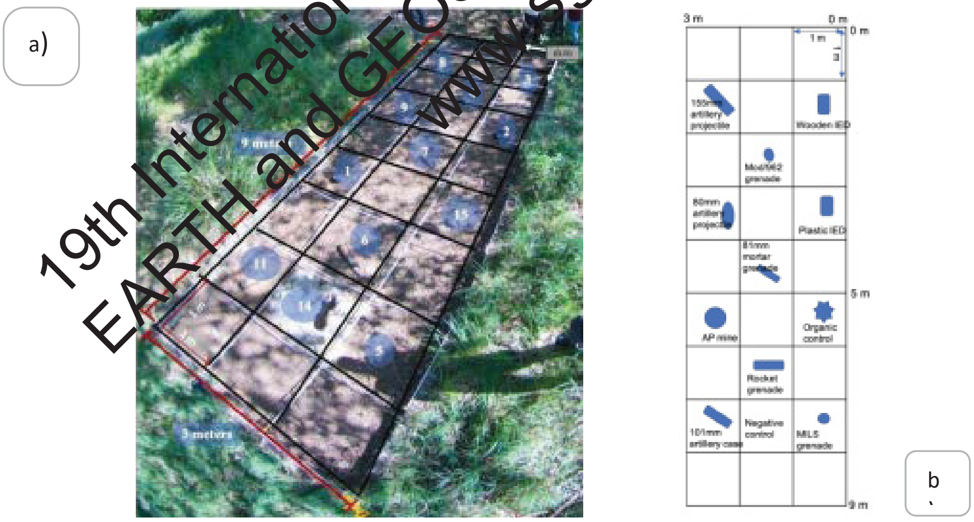

Figure 1. Sandy soil study site, in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, Porto: a) aerial image with targets' distribution and b) schematic representation of targets' distribution.

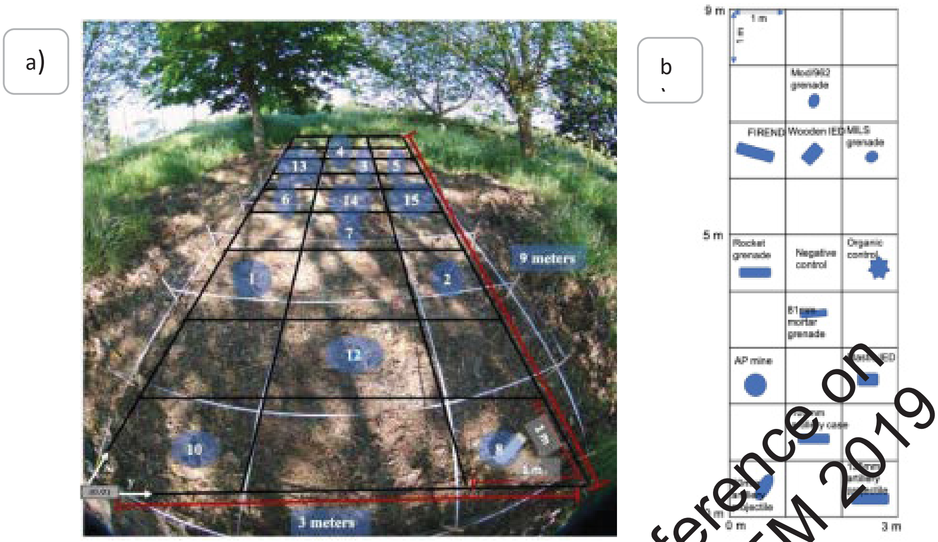

Figure 2. Clayey soil study site, in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, Porto: a) aerial image with targets' distribution and b) schematic representation of targets' distribution.

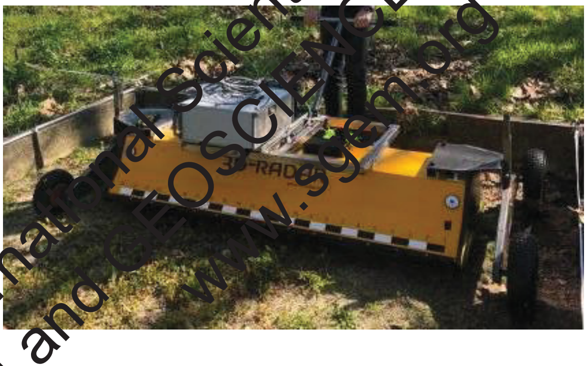

Figure 3. 3D-Radar (Geoscope-GS3F 1823).

Due to its large size, only two survey lines were performed, being enough to cover all of the study sites. GPR profiles (radargrams) were stored and then processed, using the ReflexW software, with the following processing techniques:

1. Subtract-mean (Dewow) on the 50ns of every section;
2. Background Removal;
3. Bandpass Butterworth between 500 and 1800 MHz;
4. Divergence compensation;
5. Energy decay.

Then, with the ReflexW 3D software, 3D-Cubes were constructed by interpolation between each parallel 2D profile previously processed. Time slices were then obtained, between depths of 5-10cm up to 30-40cm and signals co-related with target burial positions were analyzed.

3. RESULTS

Figures 4 and 5 presents, for each soil type, four time slices of the constructed 3D-cubes, between 5-10cm and 30-40cm of depth, with the indication of sites with signals correspondent to target burial positions (false positives are not accounted).

In the sandy soil (Figure 4), it was detected in the first time slice (a) the presence of the IED (3) in a wooden box and the 80mm artillery projectile (9); in the second time slice (b) it was detected the presence of the AP mine (1), the IED (2) in a plastic box, the rocket grenade (6), the 81mm mortar grenade (7) and the 101mm artillery case (11); in the third time slice (c) it was possible to detected the hand grenade Mod/962 (4), the MILS hand grenade (5) and the 155mm artillery projectile (8) and, at the last time slice (d) the presence of the rocket grenade (6), the 155mm artillery projectile (8) and the 80mm artillery projectile (9) were again detected, as well as the negative (14) and organic controls (15).

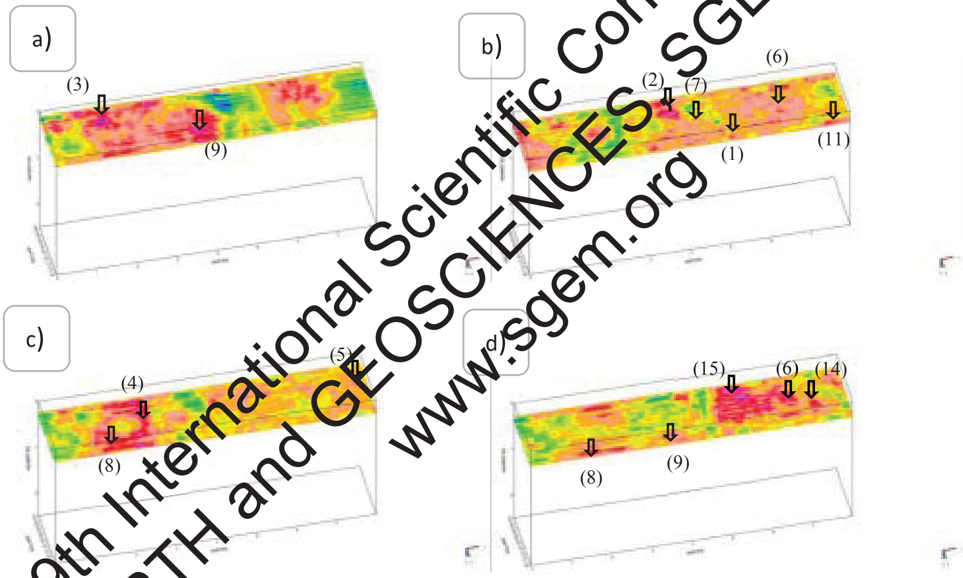

Figure 4. Four time slices of a 3D-cube, between 5-10cm up to 30-40cm in depth, for the sandy soil study site, in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, Porto. In each slice arrows indicate sites where signals could be correlated with targets' positions.

In the clayey soil type (Figure 5), in the first time slice (a) it was detected the IED (2) in a plastic box and the 81mm mortar grenade (7); in the second time slice (b) it was detected the IED (3) in a wooden box, the hand grenade Mod/962 (4), the MILS hand grenade (5), the 155mm artillery projectile (8), the 105mm artillery case (12), the FIREND (13) and the organic control (15); in the third time slice (c) it was detected the AP mine (1), the 81mm mortar grenade (7), the 60mm artillery projectile (10) and the negative control (14); in the last time slice (d) it was possible to detect again the presence of the 81mm mortar grenade (7), the 60mm artillery projectile (10) and the negative control (14), as well as the rocket grenade (6).

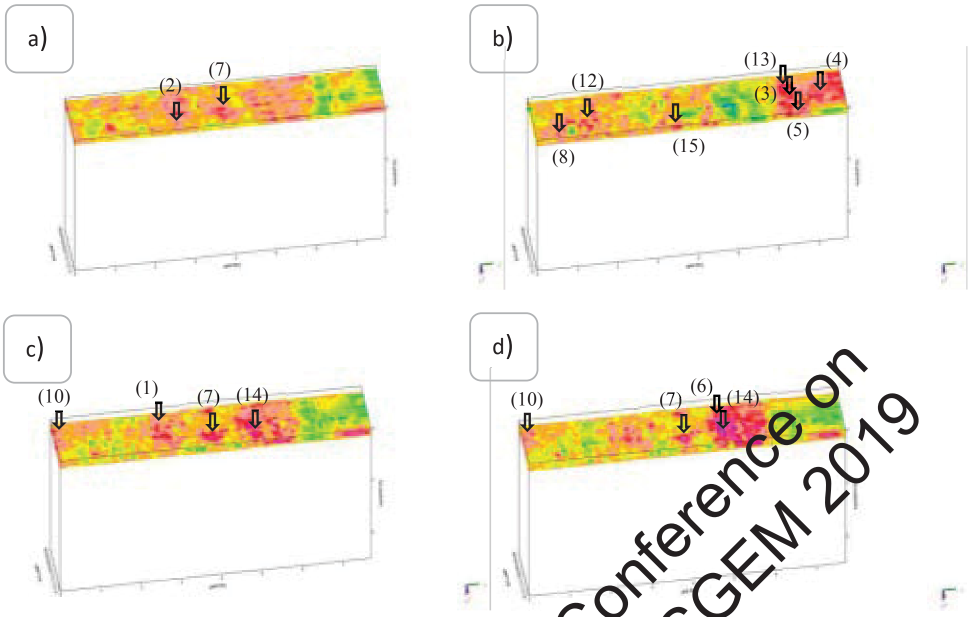

Figure 5. Four time slices of a 3D-cube, between 5-10cm up to 30-40cm in depth, for the clayey soil study site, in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, Porto. In each slice arrows indicate sites where signals could be correlated with targets' positions.

4. DISCUSSION

Although it was expected weaker performance in the clayey soil type [8], [9], both gave similar results with 100% of the explosive devices being detected.

In general, the buried explosive devices made of metal gave better and stronger responses compared with those made of plastic, which is in agreement with literature [5]. This is probably due to the high dielectric constant of metal when compared with plastic, resulting in higher amplitude reflection signals [7]. The improvised explosive device in a wooden box was easily detected in both soils, with strong GPR signal. In the study made by [7], using a GPR system with a 1.5 GHz central frequency antenna to detect a buried iron box, a plastic box and a wooden box, all targets of different materials were also detected.

Concerning the different target depths, the depth at which targets were detected does not correspond exactly to their burial depth. This could be attributed to a wrong velocity selection for depth conversion. Since almost a year has passed, after the targets burial, they could have been slightly moved by the action of rain during the burial period. Nevertheless, the 3D-Radar was able to easily detect even the hand grenades that were buried at only 5cm below the ground surface, due to its capacity in obtaining maximum resolution at shallow depths [10].

The use of high frequencies allows the achievement of high resolution images of the subsurface, that could ultimately help to guess the targets container material, their dimensions, shape, orientation and depth of burial. However, our preliminary results suggest that we can only speculate if a target has a metal or a plastic container, through the evaluation of GPR signal strength.

The negative control was detected in both soils, although this was not expected due to the long period of time that has passed between the burial and the GPR survey. This result suggest that the signals obtained for the inert explosive devices may not be only due to the object itself, but also to soil disturbance at the time of burial. This result is still useful, since it shows that even if the object is not present, the GPR technology can also notice where it was possibly buried.

5. CONCLUSION

In this study we intended to determine the capability of a 3D-ground penetrating radar in the detection of inert buried explosive devices, encompassing three variables: soil type (sandy and clayey), explosive device casing materials (metal, plastic and wood) and the burial depth (5, 15 and 30cm). These preliminary results were very promising, since all targets were detected. The results obtained in the sandy soil and clayey soil were similar, showing that the variable soil type did not have an effect on GPR performance. The explosive devices with metal casing showed the highest reflected signal while those with plastic casing were not so easily detected. Despite this, the depth, dimensions and orientation could not be correctly guessed with the obtained GPR data.

In future work, it would be important to evaluate the feasibility of explosive device detection with the 3D-Radar throughout at least a year, to also study the effect that different environmental conditions can have on GPR data acquisition.

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Quartel da Serra do Pilar: loan of the study site.

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Attachment 4. Poster Communication at the 19th International Multidisciplinary Scientific GeoConference SGEM.

Use of a 3D Ground-Penetrating radar (GPR) for detection of buried inert explosive devices

Andreia Costa[1*], Cristiano Gomes[1], Ricardo Silva[2], Diogo Rodrigues[3], José Borges[4], Fernando Almeida[3], Luís Fernandes[1,5], Rui Moura[2,6], Áurea Madureira-Carvalho[1,7]

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Abstract

A dangerous problem that a lot of countries have to face is the existence of buried explosive devices, responsible for high numbers of civilian fatalities. Their detection and removal are therefore mandatory, which has led in recent years to the development of different techniques that can ensure safer and more efficient demining operations. Geophysical techniques, since allow ground search in a non-invasive, rapid and cost-effective way, have been employed, with special interest being given to ground penetrating radar (GPR). In this field study we buried 10 and 11 different inert explosive devices in a sandy soil and a clayey soil (both with 27m^2), respectively. GPR profiles of the subsoil were obtained with a 3D-Radar, being then processed with the Reflex-Win software. 3D-cubes of the two terrains were constructed for better targets' signals visualization. Our results confirm the efficiency of this technique, since all buried inert explosive devices were detected in both soils.

USE OF A 3D GROUND-PENETRATING RADAR FOR DETECTION OF BURIED INERT EXPLOSIVE DEVICES

Andreia Costa[1*], Cristiano Gomes[1], Ricardo Silva[2], Diogo Rodrigues[3], José Borges[4], Fernando Almeida[3], Luís Fernandes[1,5], Rui Moura[2,6], Áurea Madureira-Carvalho[1,7]

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INTRODUCTION

Numerous countries all over the world suffer from high numbers of civilian victims due to buried explosive devices, including landmines, improvised explosive devices (IEDs) and unexploded ordnance (UXO).

The detection and removal of these devices is extremely important, preferably in a rapid, safe, non-invasive and non destructive manner. This has been achieved with the implementation of geophysical techniques, like ground penetrating radar (GPR), which have been successfully applied[1; 2].

GPR allows the study of subsurface features through emission and reception of electromagnetic waves, varying from frequencies of few MHz to at least 1000 MHz, resulting in formation of high resolution images of the sub-ground[3], allowing the detection of objects with dimensions of a few centimeters.

The main aim of this study was the evaluation of the feasibility of a 3D-Radar on the detection of buried explosive devices, encompassing three variables: the soil type (sandy and clayey), burial depth (5, 15 and 30cm) and casing material (metal, plastic and wood).

METHODOLOGY

This field study was performed in a facility of the Military Unit of Serra do Pilar, located in the city of Vila Nova de Gaia, Porto, Portugal. This GPR survey was performed at the Winter season of 2019 on two terrains, one with sandy soil (Figure 1) and other with clayey soil (Figure 2), both containing a similar set of buried targets. In Table 1, it can be seen the identification of the correspondent target to each number. GPR scans were made with the 3D-Radar, and data were processed with the ReflexW software.

Figure 1. Aerial image of the sandy soil study site, in the facility of the Military Unit of Serra do Pilar, with identification of the targets' burial positions, where each number corresponds to a target identified in table 1.

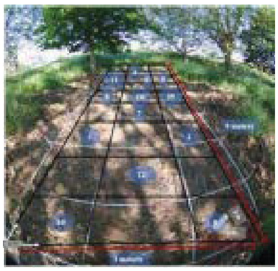
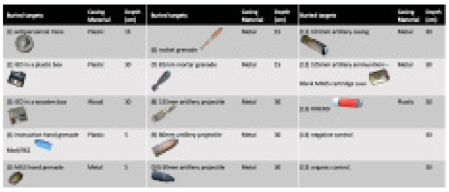


Figure 2. Aerial image of the clayey soil study site, in the facility of the Military Unit of Serra do Pilar, with identification of the targets' burial positions, where each number corresponds to a target identified in table 1.

Table 1. Identification of the 3D-GPR targets buried in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, Porto.



PRELIMINARY RESULTS

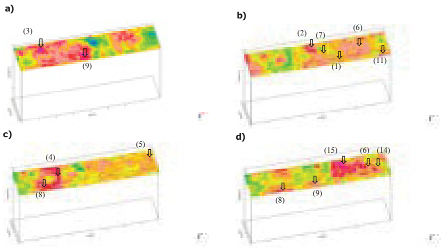


Figure 3. Four time slices of a 3D-cube, between 5-10cm up to 30-40cm in depth, for the sandy soil study site, in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, Porto. In each slice, arrows indicate sites where signals could be correlated with targets' positions.

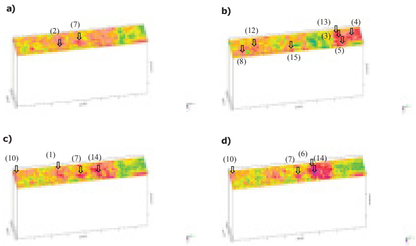


Figure 4. Four time slices of a 3D-cube, between 5-10cm up to 30-40cm in depth, for the clayey soil study site, in the facility of the Military Unit of Serra do Pilar, in Vila Nova de Gaia, Porto. In each slice, arrows indicate sites where signals could be correlated with targets' positions.

CONCLUSION

The preliminary results from this field study emphasize the fact that GPR is a good technology for buried explosive devices detection, since all targets were detected. The variables soil type and burial depth did not had an effect on GPR performance, contrary to the casing material, since explosive devices with metal casing gave stronger responses than plastic and wood explosive devices. Although the use of high frequencies, shape, size and orientation of the targets could not be guessed with these results.

An important future study would be the analysis of the effect that environmental conditions have on GPR detection capability, possibly evaluated by the performance of GPR surveys with the 3D-Radar throughout at least one year.

ACKNOWLEDGEMENTS

Project bedGPR-CESPU- 2018 financed by IINFACTS under the 2018 financing program GID-CESPU.

GNR – Destacamento de Intervenção do Porto: loan of inert explosive devices.

Quartel da Serra do Pilar: loan of the study site.

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Attachment 5. Costa's *et al.* poster communication at the IV Congresso da Associação Portuguesa de Ciências Forenses/ XIII Jornadas Científicas de Ciências do Instituto Universitário de Ciências da Saúde.

XI JORNADAS CIENTÍFICAS DO INSTITUTO UNIVERSITÁRIO DE CIÊNCIAS DA SAÚDE

IV CONGRESSO DA ASSOCIAÇÃO PORTUGUESA DE CIÊNCIAS FORENSES

POSTER

GEOPHYSICAL DETECTION OF EXPLOSIVE DEVICES BURIED IN DIFFERENT TYPES OF PORTUGUESE SOILS

Andreia Costa[1*], Cristiano Gomes[1], Ricardo Silva[2], Diogo Rodrigues[3], José Borges[4], Fernando Almeida[3], Luís Fernandes[1,5], Rui Moura[2,6], Áurea Madureira-Carvalho[1,7]

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Introduction: During some forensic investigations, buried items related to a crime are frequently encountered. Their search is generally made through large-scale ground excavations, that are manpower intensive, non-productive and can lead to criminal evidence destruction[1]. The implementation of geophysical techniques on the search for buried objects has been done in the last decades[2], proving to be more rapid and cost-effective, being additionally non-invasive and non-destructive. Buried explosive devices (BED) constitute a humanitarian problem, with many countries being affected with high numbers of civilian victims. Besides that, the process of demining is not easy, with two deminers being killed for every 1000 mines removed[3]. Ground penetrating radar (GPR) has been applied in the detection of BED with the aim of increasing the efficiency and safety of the demining operations.
Aims: The main aim of this study is to test the feasibility of BED detection, using a 2D GPR, taking into account a number of variables: environmental conditions, antenna's frequency, soil type, explosive device type and burial depth.
Material and methods: The field work was performed in Vila Nova de Gaia, in the Spring(Sp), Summer(Su), Autumn(A) and Winter (W) of 2018-2019, at a facility of the Artillery Regiment Barracks Nº5 Serra do Pilar. Two different soils (3mx9m) were selected, a sandy soil (SS) and a clayey (CS) soil, where 10 or 11 different explosive devices were buried, respectively, at depths of 5, 15 and 30cm. In each season of the year, scans were made with a 2D-Easyrad GPR using an antenna with a frequency of 300MHz. Furthermore, in Sp and A, scans were also performed using an antenna with a frequency of 100MHz. The 2D-radargrams obtained were processed using the Reflex-Win software and the percentage of detection of the BED, towards the different variables, was calculated.
Results: Handling the 300MHz antenna, the GPR clearly had a better performance when operated in good environmental conditions, in both soils. In the SS, from Sp to W, the percentage of detection was 60%, 60%, 20% and 50%, respectively; in the CS was 64%, 64%, 45% and 54%, also respectively. The enhancement of soil water content in the A, due to the intense rain on that morning, probably led to the accentuated decrease on GPR detection capacity in both soils. When comparing antennas, the one of 300MHz allowed for better results in both seasons and both soils (SSSp: 100MHz=30% + 300MHz=60%; SSA: 100MHz=10% + 300MHz=20%; CSSp: 100MHz=9% + 300MHz=64%; CSA: 100MHz=0% + 300MHz=45%). Considering all the scans, along the year (antenna 300MHz), higher percentages of detection were obtained in the CA, contradicting what has been reported so far (SS= 47,5%; CA; 56,75%). Related to the BED materials, plastics were the ones that were not totally detected in both soils, along all the year (SS=67%; CS=75%). In the SS we were never able to detect the antipersonnel mine, while, at the CS, we never detect the improvised explosive device. Finally, it was possible to verify that BED at 15 cm were more easily detected, in both soils (SS=67%; CS=91,75%). Percentages of BED detection in the SS were pretty similar at 30cm (45%) and at 5cm (50%). In the CS the BDE that were more difficult to detect were the ones buried at 5cm (25%).

Conclusions: All the variables considered affected the capacity of GPR detection. Dry environmental conditions and higher antenna frequencies are ideal for a good GPR performance. It is easier to detect BED in the CS and BED made of plastic are the ones that are more difficult to detect. Explosive devices that are buried not too shallow neither too deep, are easily detected(300MHz antenna). Blind tests, where the data analyzer does not know the burial positions of the devices, should be performed, in order to avoid bias and to simulate real events.

Acknowledgements: Project bedGPR-CESPU- 2018 financed by IINFACTS under the 2018 financing program GID-CESPU**.**

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GEOPHYSICAL DETECTION OF EXPLOSIVE DEVICES BURIED IN DIFFERENT TYPES OF PORTUGUESE SOILS

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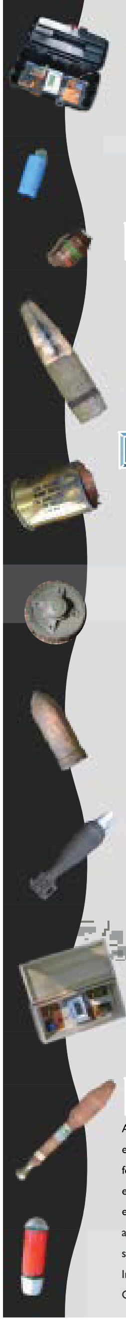


Introduction

Buried explosive devices constitute a humanitarian problem in many countries. Later recordings have in fact showed us that in 2017, due to buried landmines/explosives remnants of war, at least 2.793 people were killed, with 7.239 casualties in 49 different countries. Thus, clearance of contaminated areas is mandatory. However, this process, called demining, is very challenging and sometimes unsafe, with statistics from the United Nations (UN) stating that two deminers are killed for every 1.000 mines removed[1].

Geophysical techniques have been applied in the detection of buried objects with forensic interest, providing faster and cost-effective surveys, being additionally non-invasive and non-destructive[2]. When dealing with buried explosive devices, special interest has been given to the technology of Ground Penetrating Radar (GPR), with the aim of increasing the efficiency and safety of demining operations.

Aims

The aim of this field study was to test the feasibility of buried explosive devices detection with a 2D-GPR. The capacity of detection was evaluated taking into account five variables that can affect detection:

- Environmental conditions
- Soil type
- Frequency of the GPR antenna
- Explosive device material
- Depth of burial.

Material and methods

This field work was performed in Vila Nova de Gaia, at a facility of the Artillery Regiment Barracks N°5 Serra do Pilar, during the Spring, Summer, Autumn and Winter of 2018-2019. Two distinct soils (3mx9m) where selected, a sandy soil and a clayey soil, where 10 or 11 different explosives devices were buried, respectively, at depths of 5, 15 and 30 cm (Figure 1). In each season of the year, scans were made using the 2D-Easyrad GPR (Figure 2) with an antenna of 300MHz. Furthermore, an antenna of 100MHz was used in Spring and Autumn scans for comparison purposes. The 2D-radargrams obtained were then processed using the Reflex-Win software (Figure 3), and the explosive devices detection percentages, towards the different variables, were calculated.

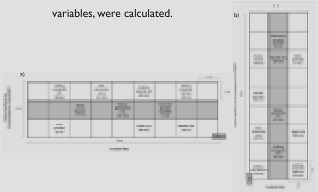
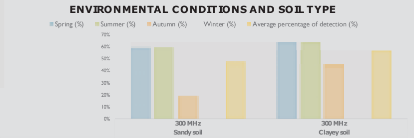


Figure 1. Schematic representation of target positions and depth of burial in each soil type: a) sandy soil and b) clayey soil. The point (0,0) represents the scan beginning. The "Football field" and "Instituto Geofísico da Universidade do Porto" are geographic references.

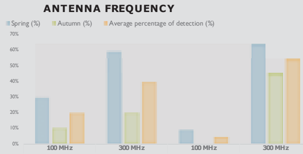
Figure 2. 2D-Easyrad GPR.

Figure 3. Example of a processed 2D-radargram.

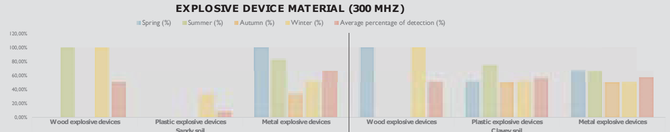
Results



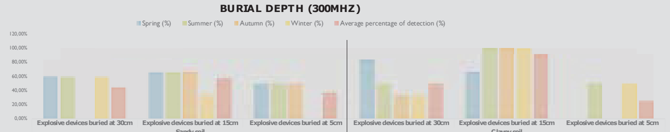
	300 MHz Sandy soil	300 MHz Clayey soil
🟦 Spring (%)	60%	64%
🟩 Summer (%)	60%	64%
🟧 Autumn (%)	20%	45%
Winter (%)	50%	54%
🟨 Average percentage of detection (%)	47,50%	56,75%



	Sandy soil		Clayey soil	
	100 MHz	300 MHz	100 MHz	300 MHz
🟦 Spring (%)	30%	60%	9%	64%
🟩 Autumn (%)	10%	20%	0%	45%
🟧 Average percentage of detection (%)	20,00%	40,00%	4,50%	54,50%



	Sandy soil			Clayey soil		
	Wood explosive devices	Plastic explosive devices	Metal explosive devices	Wood explosive devices	Plastic explosive devices	Metal explosive devices
🟦 Spring (%)	0,00%	0,00%	100,00%	100,00%	50,00%	66,67%
🟩 Summer (%)	100,00%	0,00%	83,33%	0,00%	75,00%	66,67%
🟧 Autumn (%)	0,00%	0,00%	33,33%	0,00%	50,00%	50,00%
🟨 Winter (%)	100,00%	33,33%	50,00%	100,00%	50,00%	50,00%
🟥 Average percentage of detection (%)	50,00%	8,33%	66,67%	50,00%	56,25%	58,33%



	Sandy soil			Clayey soil		
	Explosive devices buried at 30cm	Explosive devices buried at 15cm	Explosive devices buried at 5cm	Explosive devices buried at 30cm	Explosive devices buried at 15cm	Explosive devices buried at 5cm
🟦 Spring (%)	60,00%	66,67%	50,00%	83,33%	66,67%	0,00%
🟩 Summer (%)	60,00%	66,67%	50,00%	50,00%	100,00%	50,00%
🟧 Autumn (%)	0,00%	66,67%	50,00%	33,33%	100,00%	0,00%
🟨 Winter (%)	60,00%	33,33%	0,00%	33,33%	100,00%	50,00%
🟥 Average percentage of detection (%)	45,00%	58,33%	37,50%	50,00%	91,67%	25,00%

Conclusions

All the variables considered in this study had an effect on the capacity of GPR detection. Dry environmental conditions (Spring and Summer) and higher frequencies (300 MHz) are the ideal for a good GPR performance, being the clayey soil type the one where more different explosive devices were detected. In both soil types, metal explosive devices were the most easily detected. The most difficult to detect were the plastic explosive devices at the sandy soil and the wood explosive devices at the clayey soil. Explosive devices buried at 15cm (not to shallow neither too deep) are easily detected in both soil types.

In order to simulate what happens in real events of demining operations, avoiding bias, blind GPR result evaluations should be performed.

Acknowledgements:
Project bedGPR-CESPU- 2018 financed by IINFACTS under the 2018 financing program GID-CESPU.
GNR – Destacamento de Intervenção do Porto: loan of inert explosive devices.
Quartel do Regimento de Artilharia n°5 da Serra do Pilar: loan of the study site.

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Attachment 6. Gomes’s *et al.* poster communication at the IV Congresso da Associação Portuguesa de Ciências Forenses/ XIII Jornadas Científicas de Ciências do Instituto Universitário de Ciências da Saúde.

XI JORNADAS CIENTÍFICAS DO INSTITUTO UNIVERSITÁRIO DE CIÊNCIAS DA SAÚDE

IV CONGRESSO DA ASSOCIAÇÃO PORTUGUESA DE CIÊNCIAS FORENSES

POSTER

A UTILIZAÇÃO DE DOIS GEORADARES (2D E 3D) PARA DETEÇÃO E IDENTIFICAÇÃO DE ENGENHOS EXPLOSIVOS ENTERRADOS: ESTUDO COMPARATIVO

Cristiano Gomes[1*], Andreia Costa[1], Ricardo Silva[2], Diogo Rodrigues[3], José Borges[4], Fernando Almeida[3], Luís Fernandes[1,5], Rui Moura[2,6], Áurea Madureira-Carvalho[1,7]

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Introdução: Acreditar que, em Portugal, não possuímos engenhos explosivos enterrados, prontos a serem ativados, preenche-nos de um sentimento de segurança falso. Todos os países, devido às relações políticas e internacionais, devem assumir este tipo de risco. Torna-se assim necessário, por uma questão de segurança interna, a existência de capacidade para efetuar a sua deteção e posterior remoção[1]. Neste contexto, de cariz forense, torna-se determinante a aplicação de métodos geofísicos, que nos permitam elaborar protocolos para estes fins. O Georadar (GPR) é um método geofísico não invasivo, que nos permite analisar grandes áreas de terreno, num curto espaço de tempo. A sua ação consiste na emissão de uma onda eletromagnética que ao interagir com uma infraestrutura é refletida[2]. A diferença na reflexão das ondas entre o objeto e o meio envolvente, permitirá a deteção e possível identificação do artefacto enterrado, seja este artefacto um engenho explosivo, uma arma, um cadáver, ou outro[3]. Os resultados dos varrimentos por georadar são apresentados em pseudosecções (GPR 2D) ou em modelos (GPR 3D).
Objetivos: O presente trabalho tem como objetivo contribuir para a definição de um protocolo geofísico a aplicar sempre que for necessária a deteção e identificação de diferentes engenhos explosivos enterrados em território nacional.
Material e Métodos: No inverno de 2019, realizaram-se varrimentos geofísicos com um georadar 2D e um georadar 3D, em dois tipos de solo distintos (3mx9m; solo do tipo arenoso e solo do tipo argiloso), situados no Quartel da Serra do Pilar, em Vila Nova de Gaia. Previamente, em cada área de estudo, foram enterrados (5,15 e 30 cm) dois conjuntos semelhantes de engenhos explosivos inativados. O tratamento de dados foi realizado com dois programas distintos: ReflexWin 2D (GPR 2D) e ReflexWin 3D (GPR 3D).
Resultados: Os resultados obtidos foram comparados com o mapa de localização dos diferentes explosivos. Desta forma, foi possível uma melhor interpretação das alterações visíveis da corrente eletromagnética, nos varrimentos efetuados. Apesar de ter sido possível a deteção de engenhos explosivos nos dois tipos de solo, utilizando os dois equipamentos, o solo arenoso apresentou um maior número de falsos positivos, provavelmente devido à sua menor coesão. Foi ainda possível verificar que explosivos maiores são mais facilmente detetados, bem como os que são constituídos por metal (maior contraste de propriedades). Além de ter sido avaliada a capacidade de deteção dos diferentes explosivos, analisou-se também a possibilidade de identificar os mesmos. Com o GPR 3D é possível uma avaliação fidedigna da forma do material enterrado, podendo posteriormente esta informação gerar a possibilidade de identificar o mesmo, atendendo contexto do estudo. Com o GPR 2D, a forma dos materiais também pode ser obtida, no entanto, apenas por interpolação de resultados, o que torna a análise menos fiável.

Conclusão: Os diferentes GPRs podem ser utilizados para a deteção e tentativa de identificação de explosivos em solos nacionais, do tipo arenoso e argiloso. A utilização do GPR 2D trará vantagem sempre que os terrenos a estudar forem irregulares, inclinados e de pequena dimensão, uma vez que nestas situações se torna impossível o manuseamento do GPR 3D. A grande vantagem do GPR 3D está relacionada com a possibilidade de realizar varrimentos maiores, num menor intervalo de tempo, sendo estes varrimentos multifrequência, resultando numa melhor resolução dos resultados a diferentes profundidades. É necessária uma avaliação mais assertiva dos resultados obtidos para uma melhor comparação da eficiência dos dois GPRs face às variáveis em estudo, sendo crucial a realização de mais estudos semelhantes analisando as mesmas e outras variáveis (e.g. outros tipos de solo e diferentes condições climatéricas). Só após a realização destes estudos adicionais será possível a criação do protocolo de atuação que sirva o País neste e noutros contextos.

Agradecimentos: Project bedGPR-CESPU- 2018 financed by IINFACTS under the 2018 financing program GID-CESPU**.**

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3. Mitchell JK, Soga K. Fundamentals of Soil Behavior. John Wiley & Sons, Inc, 2005

A UTILIZAÇÃO DE DOIS GEORADARES (2D E 3D) PARA DETEÇÃO E IDENTIFICAÇÃO DE ENGENHOS EXPLOSIVOS ENTERRADOS: ESTUDO COMPARATIVO

é í Áure

Introdução

- A necessidade de encontrar materiais enterrados no decorrer de investigações judiciais tem sido frequente.
- Por uma questão de segurança interna do País, torna-se necessária a posse de conhecimento que permita detetar e identificar engenhos explosivos enterrados, possibilitando a sua futura correta desminação.
- A Geofísica Forense pode dar um contributo muito significativo neste contexto, permitindo o desenvolvimento de um protocolo a aplicar, sempre que necessário.

Georadar (GPR)

- O georadar (GPR) é um método geofísico não destrutivo, rápido e eficaz.
- A sua ação consiste na emissão de uma onda eletromagnética que ao interagir com uma infraestrutura é refletida.
- A diferença na reflexão das ondas entre o objeto e o meio envolvente, permitirá a deteção e possível identificação e deteção dos materiais enterrados.

2D

Fig.1

Fig.1 2D-Easyrad.

- O GPR utilizado foi o 2D-Easyrad (uma antena de emissão e uma antena de receção de 300 MHZ).
- Sistema operativo Reflex Win 2D.
- Resultados apresentados em pseudosecções e em blocos 3D. Na apresentação de resultados são estudadas as componentes X, Y e Z (X ou Y constante; Fig. 2).

Fig.2 Resultados obtidos com o sistema operativo ReflexWin 2D.

3D

Fig.x3x

Fig.3 Geoscope-GS3FTM3D.

- O GPR utilizado foi o Geoscope-GS3FTM (possui até 31 antenas e frequências de 100MHZ até 3 GHZ).
- Sistema operativo Reflex Win 3D.
- Resultados apresentados em modelos X,Y e Z (Fig.4).

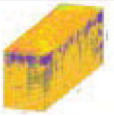


Fig.4 Resultados obtidos com o sistema operativo ReflexWin 3D.

Test-sites

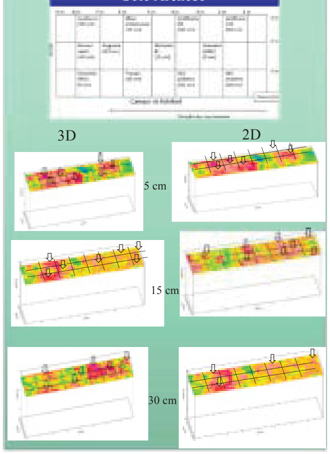
- Quartel do Regimento de Artilharia Nº5 da Serra do Pilar, Vila Nova de Gaia, Portugal.
- 2 áreas de estudo (9mx3m): solo do tipo arenoso (Fig.5) e solo do tipo argiloso (Fig. 6).
- Cada área de estudo com 10 ou 11 engenhos explosivos enterrados, respetivamente.
- Diferentes engenhos explosivos enterrados a diferentes profundidades (5,15 e 30 cm).

Fig.5 Solo do tipo arenoso

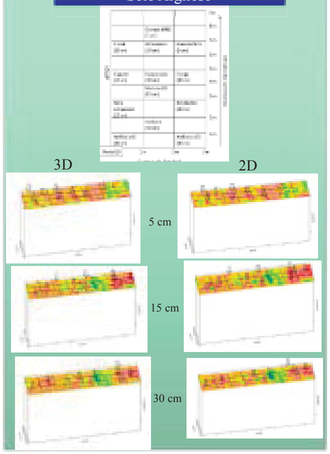
Fig.6 Solo argiloso

Resultados

Solo Arenoso



Solo Argiloso



	Tipo de Solo	
	Arenoso	Argiloso
Nº Explosivos Enterrados	10	11
GPR 2D	9/10	11/11
GPR 3D	9/10	11/11

Tipos de Material	Tipos de GPR	Tipo de Solo	
		Arenoso	Argiloso
Metal	2D	6/6	6/6
	3D	6/6	6/6
Plástico	2D	2/3	4/4
	3D	2/3	4/4
Madeira	2D	1/1	1/1
	3D	1/1	1/1

Profundidade	Tipos de GPR	Tipo de Solo	
		Arenoso	Argiloso
5 cm	2D	2/2	2/2
	3D	2/2	2/2
15 cm	2D	2/3	3/3
	3D	3/3	3/3
30 cm	2D	5/5	6/6
	3D	4/5	6/6

Conclusão

- Deteção de engenhos explosivos nos dois tipos de solo, através da utilização dos dois GPRs.
- Solo arenoso apresentou um maior número de falsos positivos, provavelmente devido à sua menor coesão.
- É possível e provável a existência de falsos negativos devido à presença de um número grande de explosivos numa área pequena.
- Explosivos maiores são mais facilmente detetados, bem como os que são constituídos por metal (maior contraste de propriedades).
- Vantagens GPR 2D: varrimentos em terrenos irregulares, inclinados e de pequena dimensão.
- Vantagens GPR 3D: possibilidade de realização de varrimentos maiores, num menor intervalo de tempo sendo estes varrimentos multifrequência, resultando numa melhor resolução dos resultados a diferentes profundidades.
- Os diferentes GPRs podem ser utilizados para a deteção e tentativa de identificação de explosivos em solos nacionais, do tipo arenoso e argiloso.
- É necessária uma avaliação mais assertiva dos resultados obtidos para melhor comparar a eficiência dos dois GPRs face às variáveis em estudo, sendo crucial a realização de mais estudos semelhantes analisando as mesmas e outras variáveis.
- Só após a realização destes estudos adicionais será possível a criação do protocolo de atuação que sirva o País neste e noutros contextos.

Agradecimentos

- IINFACTS: Programa de financiamento GID-CESPU de 2018, PI4AC: Projeto bedGPR.
- GNR - Destacamento de Intervenção do Porto: cedência de materiais explosivos inertes.
- Quartel do Regimento de Artilharia nº 5 da Serra do Pilar: cedência de espaço.

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Attachment 7. Costa´s *et al.* poster communication at the III Congresso da Associação Portuguesa de Ciências Forenses/ XII Jornadas Científicas de Ciências do Instituto Universitário de Ciências da Saúde.

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III CONGRESSO DA ASSOCIAÇÃO PORTUGUESA DE CIÊNCIAS FORENSES

POSTER

THE USE OF GROUND PENETRATING RADAR FOR DETECTION OF BURIED EXPLOSIVE DEVICES

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Some forensic investigations can be associated with hidden materials (e.g. guns, cadavers, explosive devices) that can be simply buried or occulted behind walls. Therefore, there is a crucial need of developing methods that enable them to be discovered, being the geophysical methods one of the possibilities. For instance, they have the capacity to detect and identify, for further safe removal, buried explosive devices in a non-invasive manner, which actually is a serious need in several countries[1].

Explosive devices can be classified in two major groups: i) Unexploded Ordnance (UXO) that did not explode when they were employed but still present detonation risk and ii) Improvised Explosive Devices (IEDs) that are constructed with alternative energetical materials attached to a detonation mechanism, changing the conventional operating mode[2]. Both, being possibly made of different constituents (e.g. metal/ minimum metal or plastic), can be simply laid on the soil surface or be buried within it, in a variety of environmental contexts (e.g. desert regions, mountains, jungles, urban areas)[3]. The distinction between buried UXOs/IEDs and other non-interesting metallic targets is difficult, which leads to a necessity of developing effective detection and discriminatory techniques, as electromagnetic induction (EMI) and also ground penetrating radar (GPR), that have been successfully employed in certain cases[4].

The GPR system is a non-invasive geophysical method that can be applied to a variety of different contexts, from civilian, environmental as well as military applications. It has been very used to detect buried explosive devices, due to their high frequency range, which allows higher resolution images of the subsurface to be obtained, exhibiting greater accuracy of results when compared to other methods[4]. It also has the ability to acquire data in a rapid manner and it has a good response to both, metallic and non-metallic targets. However, one disadvantage is the complexity of the acquired data, being of difficult interpretation[5]. The user needs to have a deep knowledge on the operating detection mechanism and about the peculiarities that can affect the receiving signal.

GPR uses differences in the EM material properties, namely the dielectric permittivity and the conductivity, to detect anomalies on the subsurface, as the presence of buried objects. It allows the detection of discontinuities on the subsurface through the reflection of electromagnetic (EM) waves. These waves propagate through the soil by the use of a transmitter antenna and when they meet an anomaly, they suffer dispersion, some being refracted continuing the propagation in depth, while other parts are reflected back to the surface, where the signal is received by a receiving antenna. The greater the difference between the soil and the object's EM properties, the higher the reflected signal. The GPR detection capacity can be possibly affected manly by the chosen antenna frequency and also by the propagation medium conditions, emphasizing soil water and clay content[6].

In this work, through case study compilation, we aim to demonstrate the GPR's capacity to detect buried explosive devices. Different processing methods and algorithms, that could possibly be applied to the received signals, are presented, aiming to optimize the discrimination of explosive devices buried in the subsurface. It is also shown how variables such as soil composition, device constituents and antenna frequency, can significantly affect the GPR response to targets (detection and discrimination) in a negative way.

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The use of Ground Penetrating Radar for the detection of buried explosive devices

Andreia Costa[1*], Diana Martins[1], Diogo Rodrigues[2], José Borges[3], Fernando Almeida[2], Luís Fernandes[1,4], Rui Moura[5,6], Áurea Madureira-Carvalho[1,7]

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Introduction

Ground penetrating radar (GPR) is a geophysical method that allows the detection of buried objects through the reflection of electromagnetic waves[1]. It has been very used to detect and identify buried explosive devices, in a non-invasive manner, allowing for a safe removal[2]. The high frequency range allows the formation of high resolution images of the subsurface. On the other hand, the GPR detection capacity can be greatly affected by some variables, and the obtained data can be extremely complex. Therefore, the user must have a deep knowledge concerning the GPR operating mechanism and processing techniques that can be applied to the data.

Applications

- Civil engineering: utility mapping, road/concrete inspection;
- Environmental applications: ground contamination, contaminated groundwater, investigation of underground storage tanks;
- Geology and geophysics: stratigraphy, bedrock profiling, determination of soil water content and conductivity, mineral exploration;
- Archaeology
- Law enforcement and military applications: explosives/weapons cache, forensic investigations, search and rescue operations.

Practical cases of buried explosive devices detection


Figure 1. Spatial variation in magnetic permeability in four different test sites.

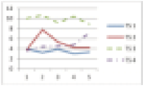


Figure 2. Spatial variation in dieletric permittivity in four different test sites.

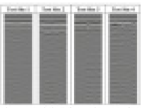


Figure 3. Variation of GPR signature of an Anti-Tank mine in separate test sites.

Effect of soil properties on an anti-tank mine reflected signal[1]


Figure 4. Two-point-three-gigahertz field data and reflection patterns obtained for a plastic anti-personnel mine (No.1-3), a metal mortar grenade (No.4-5) and a plastic anti-tank mine (No. 6-8).


Figure 5. One-gigahertz field data and reflection patterns obtained for a plastic anti-personnel mine (No.1-3), a metal mortar grenade (No.4-5) and a plastic anti-tank mine (No. 6-8).

Evaluation of a commercial GPR detection capacity and presentation of machine learning algorithms, namely logistic regression and neural network, for real-time detection[2]

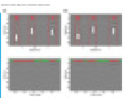


Figure 6. Detection of anti-tank and anti-personnel mines at 2.3 GHz using **(a)** logistic regression and **(b)** neural network.

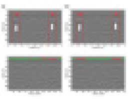
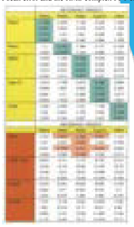


Figure 7. **(a)** Failure of the logistic regression in detecting anti-personnel mines at 2.3 GHz and **(b)** the success of the neural network for the same 2.3-GHz GPR signal.

Table 1. Results of blind testing on newly collected data (product of the RMS A-scan error and the RMS complex FFT error).



Application of algorithms for discrimination between anti-personnel landmines and clutter[3]

Detection and identification of improvised-explosive devices (IEDs) using region analysis processing for B-scan GPR image recognition and short-time matrix pencil for target identification[4]


Figure 8. B-scan image of 15-Kg gas tank buried under the road.

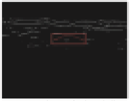


Figure 9. B-scan image after hyperbolic identification.

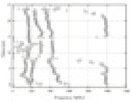


Figure 10. Extracted frequency factor from experimentation on road.

Conclusions

The GPR system has shown good performances concerning explosive devices detection, being however affected by soil properties and target characteristics[1,2]. The performance can also be influenced by the antenna frequency and the applied processing techniques[2,4] and algorithms[2,3], which should be carefully chosen. The application of machine learning algorithms can be an huge advantage, allowing an automated, fast and real-time detection, in addition to promoting false alarm rate reduction, which can also be obtained with the use of discriminator algorithms.

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Attachment 8. Martin´s *et al.* poster communication at the III Congresso da Associação Portuguesa de Ciências Forenses/ XII Jornadas Científicas de Ciências do Instituto Universitário de Ciências da Saúde.

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III CONGRESSO DA ASSOCIAÇÃO PORTUGUESA DE CIÊNCIAS FORENSES

POSTER

DETEÇÃO GEOFÍSICA DE ENGENHOS EXPLOSIVOS

Diana Martins[1*], Andreia Costa[1], Diogo Rodrigues[2], José Borges[3], Fernando Almeida[2], Luís Fernandes[1,4], Rui Moura[5,6], Áurea Madureira-Carvalho[1,7]

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Introdução: Não raras vezes, no decorrer de várias investigações forenses, torna-se necessário determinar se existem objetos (e.g. explosivos), ou cadáveres, enterrados em diversos tipos de solo. Esta deteção pretende-se rápida e não perturbadora/ invasiva da matriz geológica em análise[1]. A geofísica aplicada baseia-se num conjunto de métodos não destrutivos que permitem dar uma resposta célere e eficaz a estes quesitos que comummente se levantam.

Objetivos: O presente trabalho tem como objetivos principais a deteção de diferentes materiais enterrados em dois tipos de solo, através do uso de um georadar (GPR), e o ganho da perceção de como a tipologia de solo e as propriedades dos materiais enterrados, podem afetar a sua deteção.

Material e Métodos: Dada a necessidade de efetuar o estudo em terreno controlado, selecionaram-se dois tipos de solo (arenoso e argiloso) em terreno pertencente ao Quartel do Regimento de Artilharia Nº5 da Serra do Pilar, Vila Nova de Gaia, Portugal.
Após limpeza do terreno, em cada tipo de solo, definiu-se uma área de estudo (3mx9m). Consecutivamente, através do uso de um GPR (2D-Easyrad), realizou-se um varrimento de controlo (VC) ao longo do comprimento de cada área (9 m), em perfis paralelos e espaçados 20 cm entre si[2,3].
Posteriormente, na área de estudo do solo do tipo arenoso cavaram-se 12 buracos, tendo-se cavado um 13º buraco adicional na área de estudo do solo do tipo argiloso. Em cada área enterrou-se 1 granada Mills, 1 granada de instrução Mod/ 962, 1 granada foguete, 1 obus de morteiro 81 mm, 1 obus de artilharia (80 mm-solo arenoso; 60 mm-solo argiloso), 1 mina antipessoal, 1 invólucro de artilharia 155 mm, 1 invólucro de artilharia 101 mm (tiro real-solo arenoso; tiro de salva-solo argiloso), 1 engenho explosivo improvisado (IED) em caixa de madeira, 1 IED em caixa de plástico, 1 frango de aviário (controlo orgânico) e, voltou-se a tapar um buraco com solo, sem se ter lá colocado previamente qualquer tipo de material (controlo negativo). Adicionalmente, no solo do tipo argiloso, enterrou-se um firend de plástico. Os materiais foram maioritariamente enterrados a 30 cm de profundidade, com a exceção das granadas mills e de instrução (5 cm de profundidade) e das granadas foguete, do obus de morteiro e das minas (15 cm de profundidade).

Em cada tipo de solo foi efetuado um novo varrimento (V0) com o GPR, segundo a mesma metodologia. Todas as etapas foram fotodocumentadas a 90º face à superfície[4], tendo o estudo decorrido na Primavera de 2018.
Os dados obtidos pelo GPR foram importados para um software de processamento (Sandmeier Software REFLEXW), processados e analisados.

Resultados: Numa análise preliminar genérica, através da comparação dos volumes de dados recolhidos, antes e depois da introdução dos diferentes materiais no solo, é possível observar a perturbação do meio natural. De referir que, no local onde se enterraram os materiais de maiores dimensões, as anomalias de amplitude de sinal são mais extensas e evidentes, ainda que, não tenha sido possível detetar a forma dos referidos materiais. No local de enterro dos materiais de menor dimensão, as anomalias detetadas devem-se muito provavelmente à perturbação do solo e não à presença física dos objetos. Adicionalmente, materiais constituídos por metal originaram anomalias de sinal mais significativas. Comparando os dois tipos de solo, é possível observar algum grau de atenuação de sinal no solo argiloso.

Conclusão: Os resultados obtidos permitiram concluir que a capacidade de deteção dos diferentes materiais enterrados varia principalmente com o tamanho dos mesmos e posteriormente com os seus constituintes. Permitiu ainda verificar que a tipologia de solo influencia a capacidade de deteção do GPR, sendo esta mais evidente no solo menos coeso. O estudo será repetido em todas as estações do ano e comparado com a utilização simultânea de um GPR 3D, idêntico aos que hoje são usados pelas forças militares Norte Americanas e Britânicas.

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DETEÇÃO GEOFÍSICA DE ENGENHOS EXPLOSIVOS

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Introdução

- Durante várias investigações forenses, é necessário determinar se existem objetos (e.g. explosivos) ou cadáveres enterrados em diversos tipos de solo. Esta deteção pretende-se rápida e não invasiva da matriz geológica em análise[1].
- A análise geofísica aplicada baseia-se num conjunto de métodos não destrutivos que permitem dar uma resposta célere e eficaz.
- Os engenhos explosivos enterrados são um problema em muitos países. Assim a sua deteção e identificação é muito importante para proceder a uma remoção e destruição com menos riscos.
- Os principais objetivos deste trabalho são:
  - a deteção de diferentes materiais enterrados em dois tipos de solo, através do uso de um georadar (GPR);
  - o ganho da perceção de como a tipologia de solo e as propriedades dos materiais enterrados, podem afetar a sua deteção.

'Test-site'

- Quartel do Regimento de Artilharia Nº5 da Serra do Pilar, Vila Nova de Gaia, Portugal.
- 2 áreas de estudo – solo do tipo arenoso e argiloso
- Dimensões de cada área de estudo: 9 m x 3 m

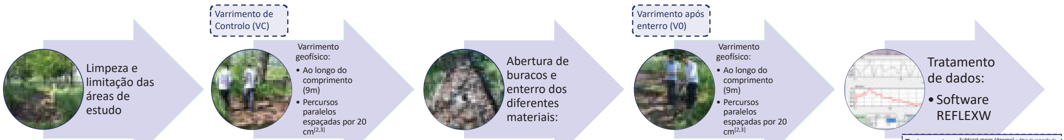
2D-Easyrad

- Conjunto de antenas de 300 MHz
- Tempo total de aquisição: 75 ns

* Necessita de computador para registar dados

Fig.1 – 2D-Easyrad

Metodologia



Limpeza e limitação das áreas de estudo

Varrimento de Controlo (VC)

Varrimento geofísico:
- Ao longo do comprimento (9m)
- Percursos paralelos espaçadas por 20 cm[2,3]

Abertura de buracos e enterro dos diferentes materiais:

Varrimento após enterro (V0)

Varrimento geofísico:
- Ao longo do comprimento (9m)
- Percursos paralelos espaçadas por 20 cm[2,3]

Tratamento de dados:
- Software REFLEXW

Tratamento de dados: Filtros e Parâmetros
- Subtract-mean (dewow) – filtro de remoção da componente de baixa frequência
- Background removal – filtro de remoção do fundo
- Bandpass butterworth - Filtro passa-banda
- Efetuar média de cada dois passos
- Correção do tempo zero (início)

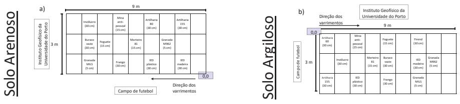


Fig.2 – Esquematização dos diferentes materiais enterrados e suas profundidades de enterro: a) no solo arenoso; b) no solo argiloso.

Todas as etapas foram fotodocumentadas (*drone Parrot Bebop 2)*. O estudo decorreu na Primavera de 2018.

Resultados

Solo Arenoso

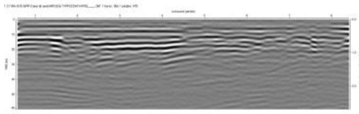


Fig. 3 - Secção 2D correspondente a um perfil longitudinais (perfil 9; 1,8m da margem)

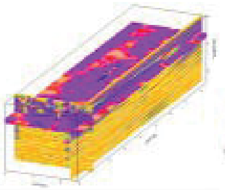


Fig. 4 - Vista 3D correspondente aos perfis longitudinais interpolados - Modelo cortado segundo 3 planos seleccionados: perpendicular, paralelo e horizontal.

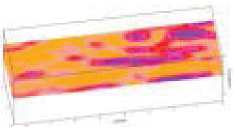


Fig. 5 - Vista 3D correspondente aos perfis longitudinais interpolados - Modelo cortado segundo o plano horizontal, numa profundidade aproximada ao aparecimentos das anomalias dos objectos enterrados.

- Perturbação do meio natural - comparação dos volumes de dados recolhidos antes e depois da introdução dos materiais no solo;

☐ Objetos maiores - anomalias de amplitude de sinal mais evidentes e mais extensas - impossibilidade de observar a forma;

☐ Materiais de menor dimensão - anomalias detetadas devido à perturbação do solo e não à sua presença física;

☐ Materiais constituídos por metal - anomalias de sinal mais significativas;

☐ Solo argiloso - algum grau de atenuação de sinal.

Conclusões

- A capacidade de deteção dos diferentes materiais enterrados varia principalmente com o seu tamanho e seus constituintes.
- A tipologia de solo influencia a capacidade de deteção do GPR (mais evidente no solo menos coeso).
- O estudo será repetido em todas as estações do ano e comparado com a utilização de um GPR 3D.

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- Quartel do Regimento de Artilharia nº 5 da Serra do Pilar: cedência de espaço.

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