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Ground Penetration Radar in Geotechnics. Advantages and Limitations

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Abstract. The use of the Ground Penetration Radar (GPR) in geotechnics presents great potential, but also relevant difficulties. This technique allows the acquisition of field data in a fast and versatile way, facilitating the interconnection between the geological studies, the geophysical characterization, the mechanical exploration and the geotechnical zoning. The depth and accuracy of data acquisition easily adapts to various situations ranging from a few centimetres to several tens of meters, changing to antennas with lower frequency. This near surface and non-destructive test method can be used almost anywhere. The continuity of the information obtained with the GPR complements the discreet and localized information obtained with the mechanical exploration. The validation of the local geological conditions using direct mechanical exploration together with the GPR imaging allows the confirmation of the parameters obtained by techniques of different nature, that once validated can allow the interpretation of areas and volumes with improved accuracy. In favourable conditions the use of the GPR can greatly help the direct mechanical exploration but the interpretation must always be done with great care and based on a good knowledge of the site characteristics. The interpretation of the GPR has in most cases many uncertainties. The research developed aimed at increasing the geotechnical characterization efficiency, using complementary techniques in order to reduce the costs and the time required to perform the geotechnical studies, ensuring that the information obtained is suitable and sufficient for the intended purposes. In a few case studies the GPR was used conjugated with trenches and the Dynamic Probing Super Heavy (DPSH) test, and allowed to enhance the individual information of each technique, increasing reliability, taking into account the importance of the geology of each site. In the geotechnical study for the rehabilitation of an ancient Villa, requiring the construction of a small auditorium in the basement and an underground garage in the garden, the GPR and the DPSH successfully allowed to define the geotechnical zoning of the surface soils and of the depth of the sandstone bedrock, as the local information obtained by the DPSH allowed to validate the GPR imaging. The presence of buried pipes and of an underground water tank were also identified by a GPR grid. In karst areas the interpretation of the GPR can be complex due to the irregular geological interface between the limestone and the residual soils filling the dissolution zones. In aeolian sands the layers structure and the change in grain size are usually well identified with the GPR imaging, which can be validated by the geological reconnaissance and the mechanical exploration. Besides the natural variation of the electromagnetic properties of the ground mass, unexpected causes like tree roots, uncontrolled fill or even previous excavations can difficult a clear interpretation of the GPR data.

1. Introduction

The Ground Penetration Radar (GPR) or Georadar, is a non-destructive technique (NDT) and non-invasive near surface site investigation and characterization technique, which relies on the penetration of an electromagnetic (EM) wave in the ground with a frequency between 10 MHz and 5000 MHz.

Increasing the frequency reduces the signal penetration but increases resolution. The frequency range between 10 and 100 MHz is suitable to investigate to a few tens of meters (deep foundations, tunnels, cavities), while the range of 100 to 1000 MHz is used to investigate on the meter scale (superficial foundations, road pavements, buried infrastructures, tunnel liners, rock blocks integrity), and above 1000 MHz to investigate on the centimetre scale (building structures, tunnel liners).

The GPR is a high resolution electromagnetic technique suitable to near surface investigations that can provide a 3-D pseudo image of the subsurface and depth estimates. It also can be used inside boreholes to examine the surrounding volume [1]. The basis for using the GPR to investigate the ground is the relation between the velocity and amplitude of the wave and the materials properties, because EM waves travel at velocities determined primarily by the material permittivity [1].

The most used layout for surface acquisition is the reflection profile. The reflected EM wave allow to interpret different materials and identify buried structures. The radargram allow to interpret and to visualize the opaque ground. According to [1] the GPR has two advantages over other non-invasive geophysical techniques: 1) The GPR provides a three dimensional pseudo-image that can easily be converted to depths that are accurate, down to a few centimetres, and 2) The GPR responds to both metallic and non-metallic objects. The GPR is an excellent tool for mapping nearly any inhomogeneity in the subsurface that is characterized by a difference in density, or porosity. The depth of the structures identified with the GPR is obtained by the reflection arrival time and the profiles can be obtained by multiple offsets.

Even after the 30 years of the first conference on GPR it is considered that a more intense use of the GPR should be the common practice [2]. The GPR can help to understand the structure and variability of the ground in a fast way, even in the field, and can provide an imaging with a resolution that can be compatible with the mapping of infrastructures.

An important goal of the use of the GPR is to allow the interpretation and validation of the distribution of the soil and rock materials, and of its internal structures, but successful results are quite dependent on a correct interpretation of the GPR data imaging. The GPR can greatly help to understand the point information obtained in boreholes or other localized site investigation, allowing to validate the interpretation between investigation points, and allowing to evaluate the distribution of the engineering geology materials.

The efficient use of the GPR require the engagement of skilled, trained and experienced professionals. To avoid inappropriate use, more training in professional education programs on NDT and GPR are needed [2].

We consider that the GPR will be a more frequently used technology in geotechnics, helping to improve the site investigation, complementing other geophysical techniques, like seismic or electric, and direct site investigation like trial pits and boreholes.

2. Examples of GPR use in geotechnics

Along the few decades of the GPR use in geotechnics, it was verified a clear growth tendency [3] but it still has great potential of grow. The GPR is quite suitable to be used in a large number of problems where its non-destructive nature is required and where it can be sensible to small variations in the ground properties. The GPR data can be quite useful if well acquired and interpreted.

A few examples of the use of the GPR in geotechnics are:

- Borehole GPR for characterization of the ground mass, of fractures, its infill and their hydraulic properties [4][5];
- Delimitation of unstable masses in slopes where geological materials are responsible for the instability[6][7];
- Detection of voids, caves and sink holes [8]–[14];

- Embankment dams and levees deterioration and erosion [15][16][15];
- Evaluation of the ground structure around tunnels and lining assessment [17]–[19];
- Foundation assessment and identification of foundation strata [6], [12], [18], [20];
- Identification of high water content in the soil [21]–[24], [25];
- Identification of tree roots [26]–[29];
- Inspection of road pavement, grade and subgrade [9];
- Liquefaction of soils in foundations [30][31];
- Location and identification of buried utilities [9], [11], [20], [32]–[37];
- Railway subgrades and ballast characterization [9], [38]–[41].

Despite the significant number of papers published it can be considered that the GPR use in geotechnics is modest, probably because of the lack of experience and confidence about the GPR and other geophysical techniques in the geotechnical community, and that engineers are more prone to believe in the direct observation of the terrain (test pit or borehole log) rather than in indirect geophysical parameters [2][42]. Borehole GPR has been used to characterize fractures and its infill and to evaluate their hydraulic properties, taking the advantage of existing a borehole to allow its use [4][5].

We would like to present a few examples of the use of the GPR in geotechnics, based on a few case studies.

The raw data of a radargram can be enhanced, increasing the visibility of the relevant structures using suitable filters. Figure 1a present the raw data, which after Dewow and background removal (figure 1b) improves the visibility of the ground structures. Both the filtering of the raw data and the interpretation must be done considering the specificities of each case under study, in order to obtain the best possible results.

3. Stratigraphic sequence evaluation

The evaluation of the stratigraphic sequence can be done using the most suitable antenna for the depth of investigation required. Using the smaller high-frequency antennae with frequencies above 500 MHz a great resolution can be obtained but the investigation depth is usually less than 8 m [43]. On the opposite, antennae with low frequencies, below 50 MHz have less resolution but can investigate depths down to 45 m. It can be considered that the best antennae frequencies for stratigraphic evaluation would be 100 MHz or 120 MHz, allowing a penetration of 15-20 m, or even deeper in unsaturated ground [43].

In figure 1-c can be observed the stratigraphic separation between Plio-Pleistocene silty sand overlaid by aeolian sands. The radargram presented was obtained with a 50 MHz antenna. Despite other higher frequencies were used (100 MHz, 250 MHz and 500 MHz) they didn´t allowed better identification of the stratigraphic interface that was located around 8 m deep. The geological mapping of slopes adjacent to the site allowed to confirm the Plio-Pleistocene silty sands. In the bottom of the valley these materials are hidden by organic soil due to the existence of farming land, at present without activity.

In figure 1 it is clearly observed that the DPSH test performed [44] allowed to validate the stratigraphic sequence interpreted with the GPR. In the aeolian sands the strength increase in a linear pattern with depth, reaching an inflection point around 8.5 m deep, corresponding to the stratigraphic transition between the aeolian sands and the Plio-Pleistocene silty sands. The reduction in strength in the stratigraphic interface could be attributed to the presence of a higher water and clay content. In the Plio-Pleistocene silty sands the strength increases with depth, but the variation of strength is higher than in the aeolian sands indicating a heterogeneous grain size distribution. Despite it is certain the presence of Jurassic limestones (Toarcian) at depths beyond 30 m, the 50 MHz GPR antenna used was unable to reached sufficient depth to identify the transition between the silty sand and the limestone. The limestones were detected during mechanical investigation works and were also observed on the beach a few hundred meters west of the site.

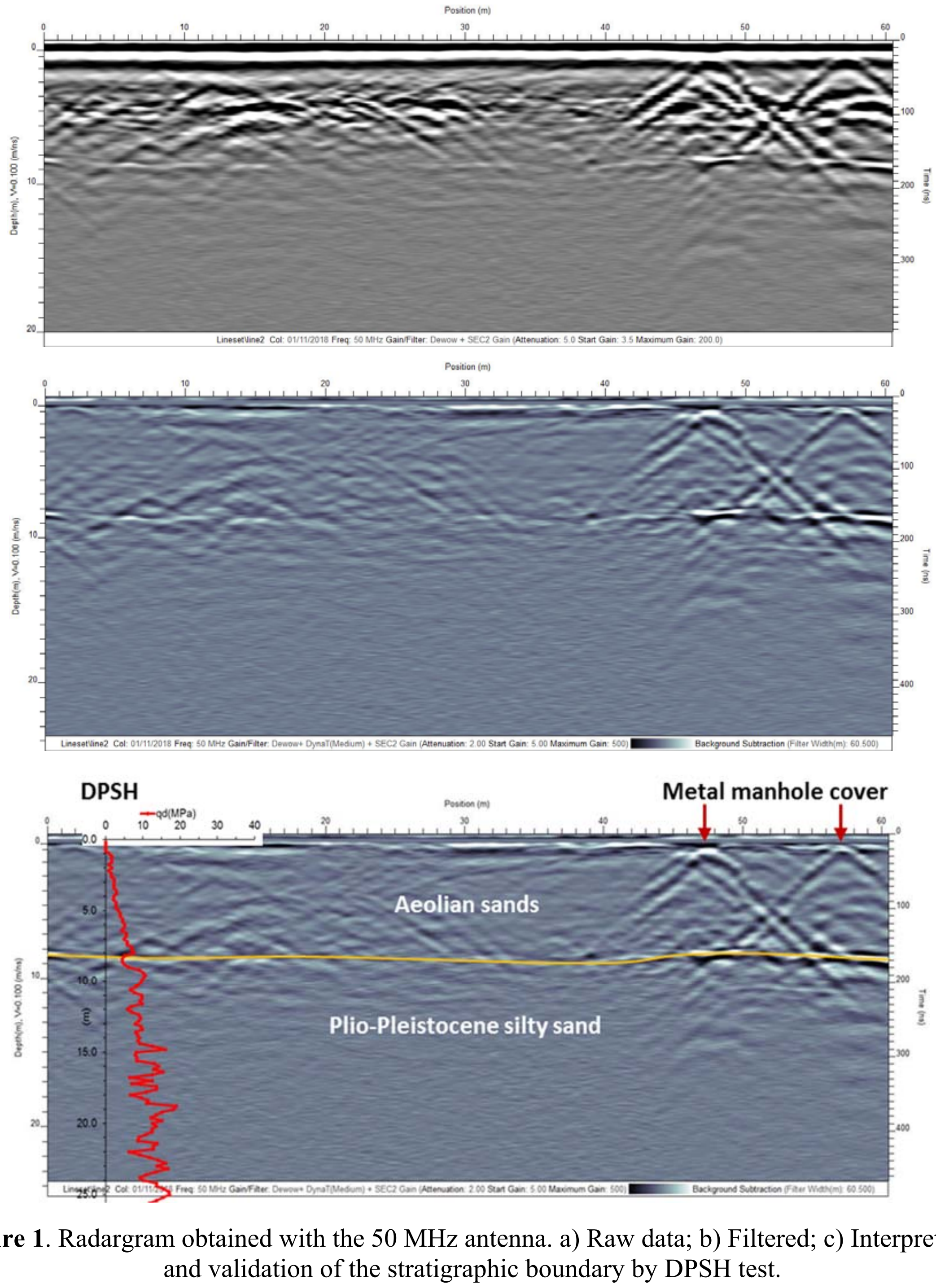

Figure 1. Radargram obtained with the 50 MHz antenna. a) Raw data; b) Filtered; c) Interpretation and validation of the stratigraphic boundary by DPSH test.

4. Aeolian sand under a paved road

Sand dunes structure, despite being constituted by grains of similar mineralogical composition, can be most of the time well understood in a radargram. The advantage of the use of the GPR is that it is a non-destructive method, which can substitute with great advantage the use of intrusive and destructive techniques like trenches or excavation that are limited in depth by the stability of the excavated sand [45]. The GPR has also the advantage of being faster to perform than digging, allowing also to interpret the structure of the dunes in 3D [45], [26]. The concentration of heavy minerals like magnetite, ilmenite, garnet or epidote accumulated during deflation lag in dunes, can create visible reflectors in radargram

[45], [43]. In aeolian sands the layers structure and the change in grain size are quite well identified with the GPR imaging, which was validated by the geological reconnaissance and the mechanical exploration.

Figure 2 correspond to a radargram obtained along a rock block paved road, constructed over aeolian sands [44]. The metal manhole covers on the surface of the road are the most visible features in the radargram, but the structure of the aeolian sands was also evidenced. Concerning the aeolian sands there are two distinct patterns, with a clear interface. The upper aeolian sands are a road fill required to level de road and was dumped over the in situ aeolian sands. Another interface well observed is the transition between the in situ aeolian sands and the older sediments dated from the Plio-Pleistocene.

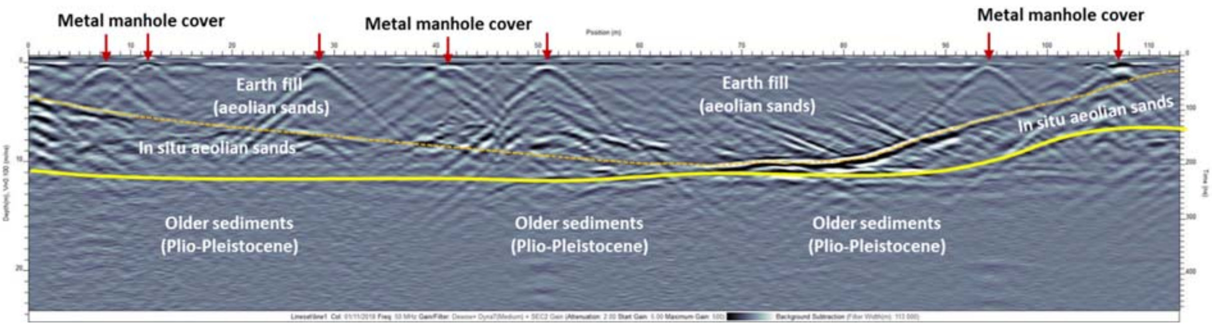

Figure 2. Interpretation of a radargram on aeolian sands under a rock block paved road.

5. Buried utilities

Mainly in urban areas a large number of utilities can be found underground, along roads or sidewalks, parking areas, buildings or even in open field. Frequently the exact location or characteristics of these utilities are unknown. Some examples are telecommunication cables, gas pipes, water pipes (low and high pressure), energy cables, sewers, water drainage systems, tanks and drums. The complexity of the terrain where these utilities are located is frequently a serious obstacle to its precise identification and detection [18][46]. The use of grids allowing to create a 3D imaging is usually a more efficient way to identify utilities than the use of single radargram sections that only allow a point intersection of the utilities. With suitable conditions the 3D imaging can allow to draw the path of the utility in a specific area and the use of slices at increasing depth allow a real understanding of the utility position inside the terrain volume analysed.

During a GPR line survey a flat reverberated reflection was identified as presented in figure 3 [47]. To improve the characterization of the structure a grid was performed and the results presented in figure 4 allowed to identify a buried concrete water tank. A slice plan at 0.6 m depth (figure 4a) intersects the upper concrete slab. The radargram crossing the centre of the tank is presented on figure 4b. The GPR data allowed to detect and identify the previously unknown tank and to determine the approximate volume of the tank. The use of filters can improve the visibility of structures as can be viewed in figure 4 that was processed using Dewow, Background subtraction, Migration, Envelope and Amplitude Equalization.

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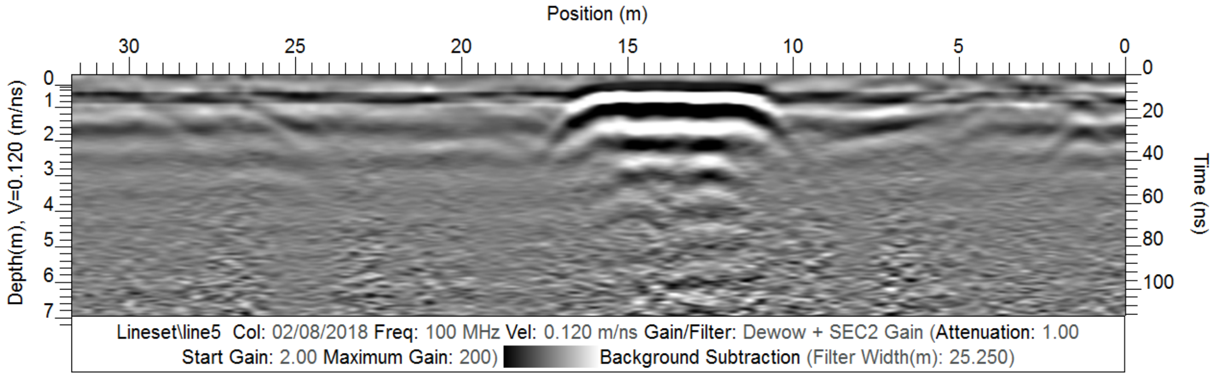

Figure 3. Flat reflection with reverberation detected in the radargram.

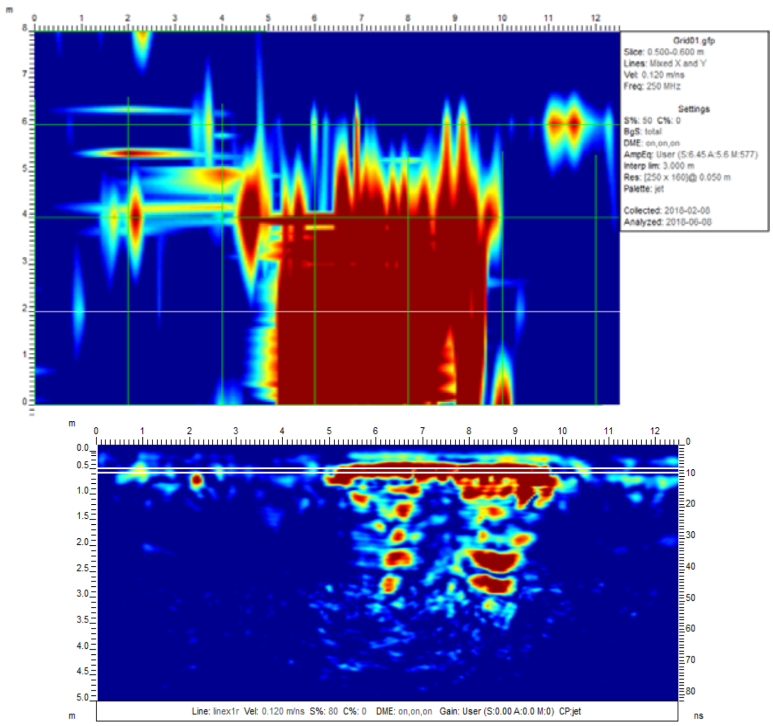

Figure 4. GPR grid used to analyze in detail the structure detected in figure 3, corresponding to a buried tank. a) Slice view at 0.6m depth at the level of the top concrete slab. b) Vertical line scan crossing the centre of the tank. Data processed using Dewow, Background subtraction, Migration, Envelope and Amplitude Equalization.

Leakage in water pipes, sewers and drainage systems can cause several problems related to internal erosion, wash-out or the triggering of landslides. These anomalies tend to increase with time and its identification is most of the times difficult to achieve in the field due to unpredicted variations in the water content and to the structures present in the terrain, but more easily identified in laboratory controlled conditions [48].

6. Geotechnical zoning

The preparation of the geotechnical zoning is a relevant task during the development of the terrain study for engineering projects. A geotechnical zone can be defined by its volume distribution, considering a quasi-homogeneous zone, characterized by average geotechnical parameters, with well-defined dispersion values. The definition of geotechnical zones has to take in account the eventual presence of singularities, like faults, weak seams, thin soft strata, etc., that can be critical to the stability and safety of the engineering structure.

The number of publications reporting the use of the GPR in assisting the preparation of the geotechnical zoning for construction can be considered reduced [6], [12], [18], [20]. During the preparation of the geotechnical study the detection of underground utilities [9], [11], [20], [32]–[37] is more frequently reported.

In the geotechnical study for the rehabilitation of an ancient Villa, requiring the construction of a small auditorium in the basement and of an underground garage in the garden, the GPR and the DPSH successfully allowed to define the distribution of the superficial soils and the depth of the bedrock. The surface layering of the soil cover was clearly detected by the GPR, but at greater depth the separation between the soil and the bedrock is not easily understood based on the line scan. The improved definition of the boundary between the soil cover and the sandstone bedrock greatly benefited of the use of the GPR imaging allowing to understand the continuity of the local information obtained by the DPSH. The differentiation between a silica sandstone of the bedrock and the soil cover, mainly weathered sandstone, is shown in figure 5. This unclear differentiation could be a consequence of the similarity of dielectric properties of the soil developed from the weathering of the sandstone bedrock and of the properties of the sandstone bedrock. On the opposite the separation between soil and rock is easily determined based on the results of the Dynamic Probing Super Heavy (DPSH) tests performed (figure 5) [47]. The geotechnical zoning was improved using different tests that could clarify the doubts based on a single test method.

As already described the identification of underground utilities, despite they are not in the aim of the geotechnical zoning, is very important because its identification allows to alert the designers and contractors for the implications that the presence of these utilities implies to the construction activities. The enrichment of information on the ground characteristics and utilities present in a foundation terrain is always very useful for the planning and construction activities, increasing safety and reducing both the time of construction and costs.

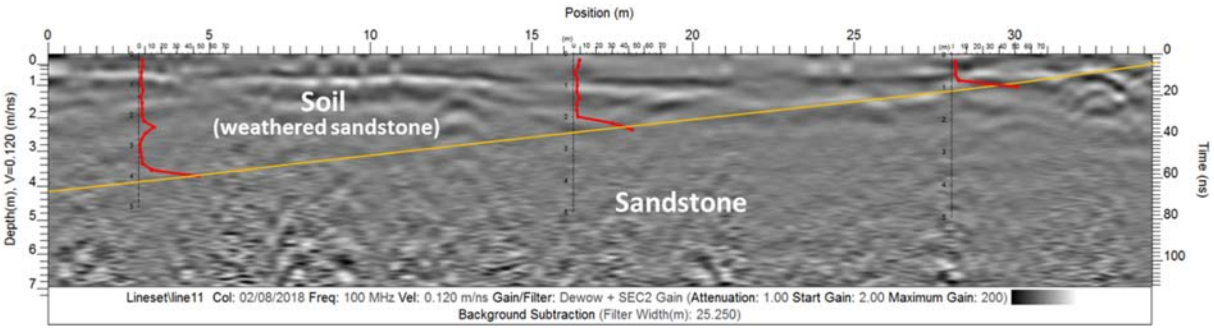

Figure 5. Unclear differentiation by the GPR between a silica sandstone (bedrock) and the soil cover of weathered sandstone. The use of the DPSH tests helped defining the interface.

7. Karstification

The engineering geology of karst areas can be quite complex and difficult to predict. One of the main goals of the engineering geology studies is to understand the distribution and interface between the rock mass and the residual soil (terra rossa) which can have an important clay content and that is characteristic of most karst structures [49], [50], [50]. The detection of voids and caves is also a relevant goal as they can present unpredicted location and dimensions, implying specific engineering geology challenges. Despite the GPR is quite useful to determine the presence of karst structures [49], [51], its interpretation can be complex due to the irregular and frequently unexpected geological interface between the limestone and the residual soils filling the dissolution zones.

At Rabaçal the karstification is dominantly superficial, frequently with a well-defined local pattern as illustrated if figure 6 [52]. The limestone pavement pattern (figure 6a) develop along the dissolution planes is mainly controlled by the orthogonal sub vertical joints. The limestone is exposed following the removal of the surface residual soils having a thickness of usually below 1 m, and that are visible on the background of figure 6b, above the striped and weathered limestone in the foreground. The residual soil cover has large number of limestone fragments, since gravel to boulder dimensions, which show a layered image on the GPR scan line. Below the cover soils, already in the karst limestone, the heterogeneity of the limestone pavement structure was detected by the GPR, delivering an image of an almost random pattern of block-like structures with the spaces between blocks filled by soils (figure 7). This pattern is visible mainly on the right side of figure 7, presenting a large number of systematic hyperbolas due to the contrast between the limestone blocks and the surrounding residual soil.

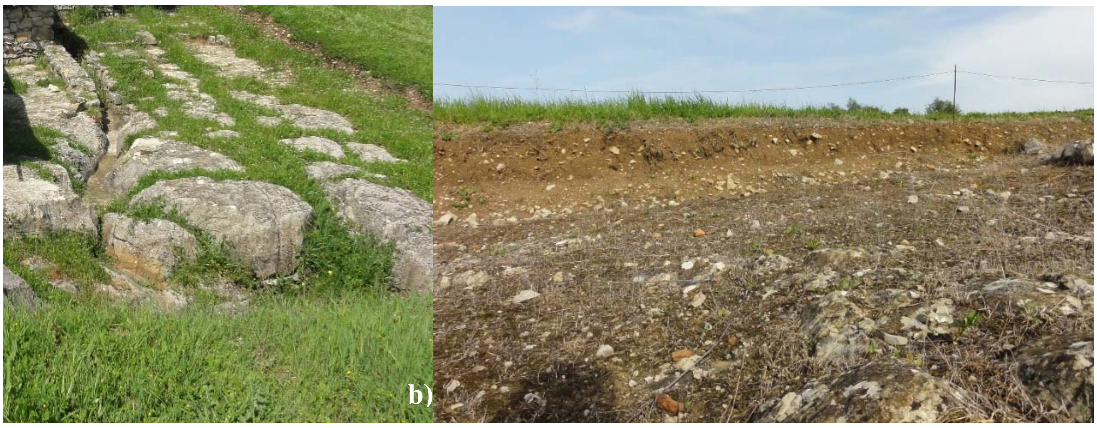

Figure 6. Superficial karst patterns identified at Rabaçal. a) Limestone pavement pattern developed along dissolution planes, controlled by orthogonal sub vertical joints. The limestone is exposed after the removal of the residual cover soils. b) Moderate thickness of residual soils, usually below 1 m, visible on the background, over the striped weathered limestone.

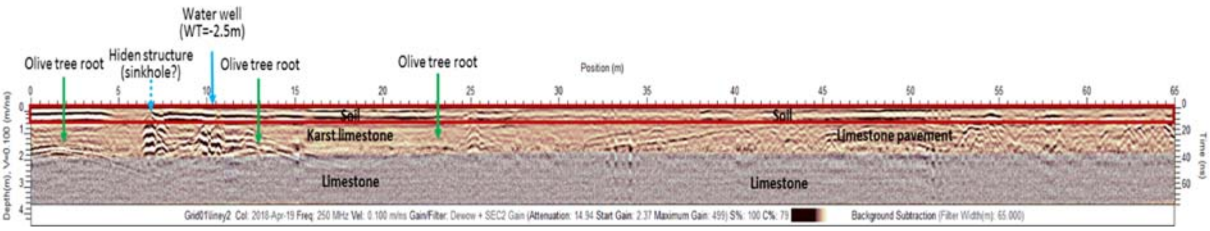

Figure 7. Interpreted GPR section showing the soil cover (on top), limestone pavement (at right), olive tree roots and water well (at left). See also figure 8.

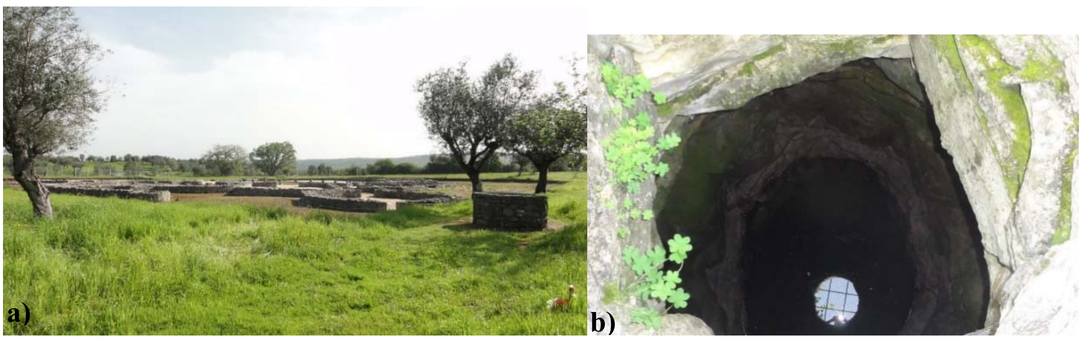

Figure 8. **a)** Surface view of the profile of figure 7, showing the olive trees and the water well. **b)** View inside the water well showing compact limestone and the reflection on water table.

8. Tree roots

Tree roots are often present in natural ground but also in geotechnical works like embankments, pavements, parking areas, sidewalks, etc., creation frequently difficulties [29] due to the cracking, lifting and waving of pavements [28], damaging of utilities [45] or simply difficulties to identify tree roots separately from other buried utilities.

The size of roots is an important aspect in their detection by the GPR [28] due to the differences of dielectric properties between coarse roots and the surrounding soil. Thick roots tend to present two sets of reflected signals generated in the upper and lower surfaces [26]. The random distribution of the tree roots in the field often increases the difficulty to accurately identify the roots with the GPR. An accurate determination of tree roots in 60% of the cases, with the tree root depth measurement accurately determined in all successful cases with an error below 15% was reported by [28].

In figure 7 the location of the olive tree roots was facilitated by the surface observation (figure 8). The pattern for the tree roots was limited by the geological distribution of the karst limestone below the surface soils, obliging the roots to spread above the compact limestone, generating an almost horizontal pattern.

Despite these successes it can be considered that there are still problems in accurate root depth and size measurements using GPR, and that the nature of the soils can increase difficulties, like clayey soils or high water content. According to [28], increasing permeable pavement sub-base depths may lead to less pavement damage by tree roots thereby preventing future trip hazards and avoiding costly repairs.

9. Conclusions

The research developed aimed at increasing the GPR use in geotechnics, complementing other geotechnical characterization techniques in order to reduce the cost and the time required to perform the geotechnical study, but ensuring safety.

The GPR was used conjugated with the Dynamic Probing Super Heavy (DPSH) tests and with trenches, allowing to enhance the individual information of each technique, increasing reliability if taking into account the importance of the geology in each site. The GPR and the DPSH successfully allowed to define the distribution of fills, cover soils and of the depth of the bedrock as the local information obtained by the DPSH allowed to validate the GPR imaging. The presence of buried pipes and of an underground tank for rain water storage was also efficiently identified using a GPR grid.

In aeolian sands the layers structure and the change in grain size was well identified with the GPR imaging, which was validated by the geological reconnaissance and the mechanical exploration.

In karst areas the interpretation of the GPR can be complex due to the irregular interface between the limestone and the residual soils filling the dissolution zones. Despite that the GPR is quite useful to help identify the karst structures. Other aspects like tree roots, uncontrolled fill or even previous excavations can difficult a clear interpretation of the GPR data.

The GPR is a useful technique that will be more used in the future providing great contributions to more reliable geotechnical studies.

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