Predictive Mapping of Soil Geophysical Properties for GPR Utility Location Surveys

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Abstract —**Ground Penetrating Radar (GPR) offers a relatively rapid and non-intrusive method for detecting buried utilities. In congested urban environments, where most buried utilities are to be found, this translates into significantly reduced disruption to highway users and reduced risk for developers and contractors. However, GPR performance varies significantly over large geographical areas due to variations in soil type and water content. Therefore, GPR utility location can be perceived by clients as largely hit-and-miss in terms of its planning, as full information may not be known in advance for determination of expected penetration depths and the most appropriate signal frequency ranges. This paper details the current state of predictive soil electromagnetic property mapping, from which it will be concluded that existing geotechnical databases and techniques can provide useful data on which to base such maps. In so doing, it also extends knowledge on the efficacy of predictive mapping for potential use internationally.**

Index Terms **— Soil, electromagnetic properties, signal velocity, geophysical mapping, Mapping the Underworld, ORFEUS, British Geological Survey.**

I. Introduction

The location of utilities using Ground Penetrating Radar (GPR) provides the opportunity for relatively rapid and non-intrusive mapping of buried infrastructure. The speed with which a survey can be undertaken, together with the potential for future improvements in GPR to negate the need for truthing excavations, allows for reduced utility location costs, reduced disruption to highway users and less emissions due to resulting highway congestion. In essence, when used effectively, GPR could be considered to contribute to the three main pillars of a sustainable model: environment, society and finance. The potential contribution of GPR to mitigate the direct and indirect costs associated with street works, which have been estimated to be £7 billion per annum in the UK alone [1], comprising £1.5 billion in direct construction costs and as much as £5.5 billion in social costs.

However, current technology does not allow for GPR systems that can see all features, at all depths, in all soils and, according to a recent survey, potentially even to an accuracy acceptable to utility-location stakeholders [2]. For instance, the signal velocity and penetration depth of GPR are determined by the antenna frequency and the electrical conductivity of the ground being profiled. At a given frequency, the attenuation of electromagnetic energy increases with increasing moisture content [3], and the velocity decreases. As electrical conductivity is directly related to the amount, distribution, chemical composition, and phase (liquid, solid, or gas) of the soil water [4], and the clay and soluble salt contents, many significant variables conspire against effective GPR use in many soils. The importance of water content on attenuation is demonstrated in Figure 1 which shows GPR tests carried out by the ORFEUS [5] project, during measurement above a water pipeline near the city of Brno, in the Czech Republic. In this example, addition of water can be seen to effectively remove reflections from the GPR plots.

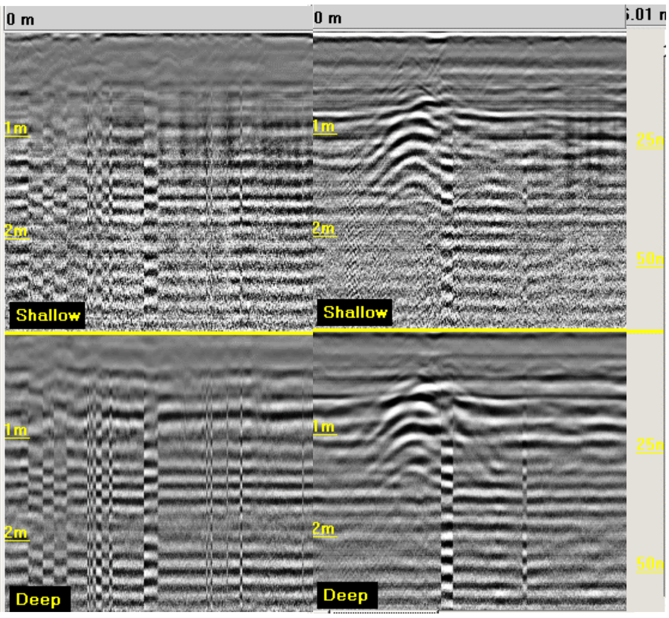

Figure 1 – Attenuation of GPR signals: 250 MHz (deep), 700 MHz (shallow), in wet loamy soil (left side) and at the natural water content (right side).

Even current projects designed to provide radical improvements, such as the ORFEUS GPR system, and the surface and in-pipe GPR antenna arrays being developed by the Mapping the Underworld (MTU) project [6], while pushing the boundaries of technology much further forward, will still have difficulties operating in very poor soil conditions. Therefore, to achieve the highest standards of GPR use, knowledge of GPR soil suitability is a critical factor in the planning and interpretation of utility location surveys.

In order to achieve the goals of predicting and mapping the effects of soils on GPR signals, various initiatives are ongoing, including those involving MTU, the British Geological Survey (BGS) and ORFEUS. MTU has, since 2005, been developing and conducting tests to investigate links between geotechnical and electromagnetic effects in soils. This has led to the formulation of an initial concept for inter-prediction of these properties to extend previous research described in the literature. The work of the BGS then brings with it a significant depth of knowledge on geotechnical and geological soil properties in the UK, and geospatial databases of such data. The ORFEUS team, for its part, has also been considering how geotechnical tests could be used to predict GPR performance and, equally importantly, has considerable expertise on the effects of soils on high-performance GPR systems. These initiatives, when considered together, provide the basis for radically improving the quality of soil data available to GPR practitioners in any nation where suitable geotechnical data are available.

This paper will start by discussing current research focussing on the prediction of electromagnetic signal velocities in fine-grained soils. Therefore, the potential for using geotechnical and geological databases for mapping these soil properties is illustrated using those maintained by the BGS. The paper will then conclude that geotechnical data, and related geospatial databases, provide a new opportunity to intelligently incorporate data on prevailing soil conditions into the planning and interpretation of GPR utility location surveys.

II. Predicting Soil Electromagnetic Properties

Utilities are usually installed at shallow depths in soils which may, for instance, be represented by Quaternary or Tertiary sediments as gravels sands, loams, loesses or clays. Currently, development of the soil mapping initiative is concentrating on the signal velocity variations that occur in predominantly silty and clayey soils, as these are generally considered the most difficult to penetrate using GPR, at varying water contents. Such variations in a heavy London Clay are illustrated in Figure 2 [7] for common GPR frequencies, and it can be seen that, even for a single soil, there is a significant amount of variation in signal velocity. However, it should be noted that the large variations in signal velocities covered by Figure 2 are not necessarily of significant relevance to field geophysics. Dry clay soils are not generally found in the field within the burial depths of most utilities, and from a geotechnical perspective they would commonly be expected to have a water content between the plastic and liquid limits [8]. These limits represent the two extremes of a soil that is dry, and non-plastic, enough to start to break up when rolled into thin sections (the plastic limit) and wet enough to start to act as a viscous liquid (the liquid limit). They are respectively marked W_P and W_L on Figure 2. When the signal velocity between these limits is considered, it can be seen that there is a much smaller potential for variation in signal velocity within the potential range of field water contents. While these limits represent gravimetric water contents, they can be related to volumetric values through knowledge of the dry densities of soils.

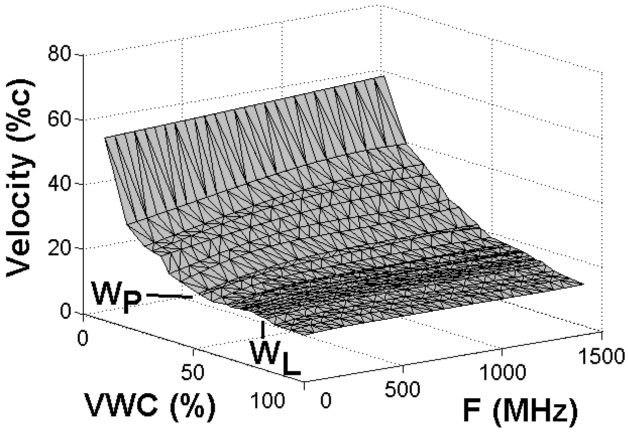

Figure 2 - Variations in signal velocity, for a London Clay, due to signal frequency and volumetric water content between 100MHz and 1.5GHz [7].

Understanding these limits (known as Atterberg Limits) allows for comparison of the effects of a variety of clay soils on signal velocities. This is illustrated in Figure 3, which shows velocities in eleven soils at their liquid limits measured using Quarter-Wavelength Analysis (QWA) [9]. Of particular note is that these soils show a relationship, between water content and velocity, close to linear at high frequencies, lower frequencies showing variations also with frequency known as electromagnetic dispersion. It is important to note that the variations in signal velocity due to water content are, in general, of greater significance than those due to dispersion, at least at the liquid limit. Also, as can be seen from Figure 3, it is important to remember that clays can remain in a plastic state at very high water contents: potentially to more than 90% by volume, as the figure illustrates.

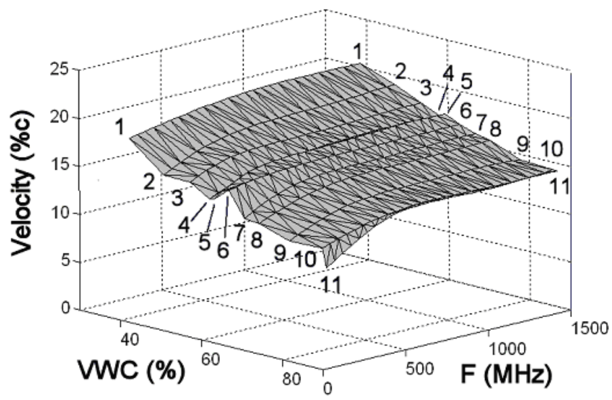

Figure 3 - Signal velocities in eleven soils (1 to 11) at the liquid limit (100MHz to 1.5GHz): the soil shown in Figure 1 is No. 7 [7].

Although dispersion may not be as important a factor in signal velocity determination as water content, its effects in attenuating GPR signals requires that it be considered in detail [10]. It is widely understood that heavy clay soils have the greatest impact on GPR signals, causing significant attenuation that may limit signal penetration to just a few tens of centimetres. It is also known that these effects are significantly greater where the soil has a large proportion of very small grains (e.g. clays and silts) compared to larger soil grains (e.g. sand) [11].

When considered in detail, clays are complex structures comprising microscopic sheets of minerals which, per unit of surface area, have very similar surface charges [12]. However, in very simple terms, clays can be split into those where the sheets form a larger particle with many sheets face to face, and those where the sheets exist more individually, the former giving rise to water both between the sheets and around the particle, the latter predominantly being associated with water around sheets. This simplistic model can, of course, be influenced by sedimentary and consolidation processes.

Soils with large amounts of inter-sheet water, such as those containing significant amounts of smectite clays, will generally exhibit significant shrinking and swelling effects with variations in water content. The distribution of water molecules, and how they interact within the clay matrix, has a significant effect on its properties [13] and may vary between inter-sheet and inter-particle locations. It might, therefore, be expected to give rise to variations in electromagnetic properties. The potential for this can be seen in Figure 4, which shows the relationship between the geotechnical parameter of percentage linear shrinkage and the magnitude of the dispersion (the difference in apparent permittivity between values at 100MHz and 1GHz) for nine of the soils shown in Figure 3. Linear shrinkage essentially measures the reduction in length of a soil specimen as it dries from the liquid limit to a zero water content, and higher values are generally considered to relate to soils with significant inter-sheet water. From the simple linear fit of Figure 4, it is apparent that there is some relationship between the magnitude of dispersion and the shrink-swell behaviour of fine-grained soils.

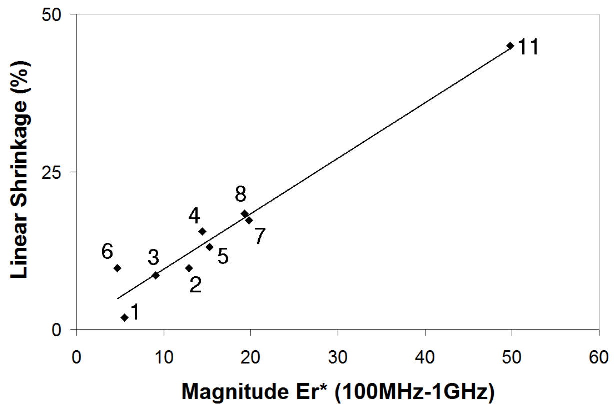

Figure 4 – Linear shrinkage in nine soils (1 to 8 and 11) at their liquid limit in relation to the magnitude of the dispersion between 100MHz and 1GHz.

There is also evidence that the average electromagnetic properties of pore water may be constant at high frequencies, regardless of changes in water content significantly changing the amount of soil particles per unit of volume [7]. Therefore, it is possible that the two types of water described above may be a significant aspect of the 'bound' and 'free' water often used to describe variations in soil electromagnetic properties with changes in water content. Further research is currently being carried out more fully to explore the dynamics of the pore water properties, together with their potential sensitivity to variations in temperature. Also, it should be noted that significant soil magnetic properties will influence the quality of prediction [14] and so work has also been ongoing to characterise their potential effects [15].

The above consideration of the effects of soils on GPR signals can be seen to provide a broad-brush method of predicting those effects where suitable geotechnical data are available. As will be seen in the next section, such data are available in database form, at least for much of the UK and potentially for urbanised areas of many developed and developing nations. However, where it is not available, it must be noted that other methods exist for GPR soil suitability prediction and mapping [16] that can take advantage of geotechnical and geological data, and which can be used in parallel with the methods illustrated in this paper.

III. Available Geotechnical Data for Mapping

In 1992 the Association of Geotechnical and Geoenvironmental Specialists (AGS) established a common Data Interchange Format (DIF) for the storage and transfer of electronic data from UK site investigation reports. Electronic databases were modified to this format and a key change included litho-stratigraphic information being associated with depth intervals down a borehole. When associated with harmonised litho-stratigraphic descriptions, this storage format has opened up the possibility for the attribution of litho-stratigraphy, and thus related geotechnical data within 3D geo-spatial models of the sub-surface. This approach allows formation studies, for example of fine soils and mudstones with an extensive UK distribution, and thus of key significance to engineers and planners.

The UK's National Geotechnical Properties Database (NGPD) is managed by the BGS and contains information on many relevant UK soil and rock formations [17]. Property attribution of 3D geo-spatial models allows ground behaviour assessments in UK geographic zones of strategic importance. Current research includes the use of plasticity values stored in the NGPD in a study of the shrink-swell behaviour of UK clays and mudrocks which, as previously described, is a significant factor in GPR soil suitability. Dispersion-related differences in signal velocities may be of significance to future improved wide-band GPR systems able to penetrate clays to significant depths. Such shrink-swell information and databases can also be applied to infer shrink-swell risk at locations where high velocity-dispersion is encountered.

Currently, BGS has three projects relating to shrinkage and swelling of clay soils. One of these, the Ground Shrinkage Hazards project, has three main aims that have direct relevance to GPR soil suitability prediction and mapping:

- To define and describe the distribution, properties and behaviour of shrink-swell susceptible clays and mudrocks;
- To model their behaviour across the UK and the resultant risk to properties and infrastructure;
- To develop new technologies and to improve upon accepted shrink-swell testing methodologies.

The Ground Shrinkage Hazards project also provides valuable additional inputs to the NGPD, and uses the data within it to create 3-D models of the volume change potential of soils. Formation based studies have included the Gault clay, Mercia Mudstone, Lambeth Group (Reading clays), Lias Clay, London Clay and Weald Clay, ensuring good UK data coverage.

The geographic extent of such studies depends upon the distribution of available data. For example, Figure 5(a) shows the geographical extent of plasticity data held in the NGPD, which relates to the Atterberg Limits, and it can be seen that this covers the major population centres where most utilities will be located. Considering the full database in Figure 5(b), it can be seen that even more data are available if other geotechnical parameters, including shrinkage potential, are taken advantage of. However, further data would be available to supplement the NGPD if land developers could be encouraged to provide any relevant site investigation data in future.

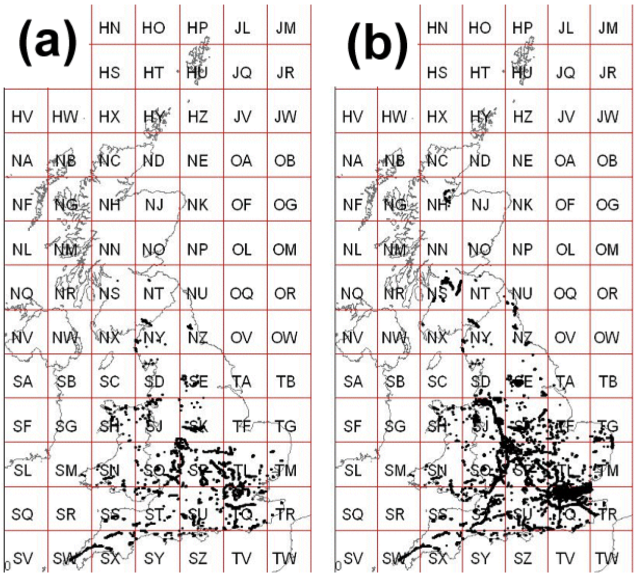

Figure 5. UK coverage of the NGPD - (a) Distribution of plasticity data and (b) Complete data coverage [7].

In considering the use of the NGPD, and other BGS databases, it is important to consider whether the data available are adequate for use in GPR soil suitability assessment. One criticism that could be made is that geotechnical properties, such as Atterberg Limits, are generally measured on samples containing only the fraction of soil less than, or equal to, 425μm in size, but soils may often be much coarser. This is investigated in Figure 6, based on BGS data, and indicates that the proportion of such fine grains is very variable. However, as indicated by the line of best fit, fine grained particles often dominate the UK soils they are found in, especially in high liquid limit soils that may have the greatest influence on GPR, ensuring that correction of predictions for the presence of coarser grains will be based generally on the minority soil fraction. For such corrections, the BGS datasets also contain details of the proportions of these larger soil grains.

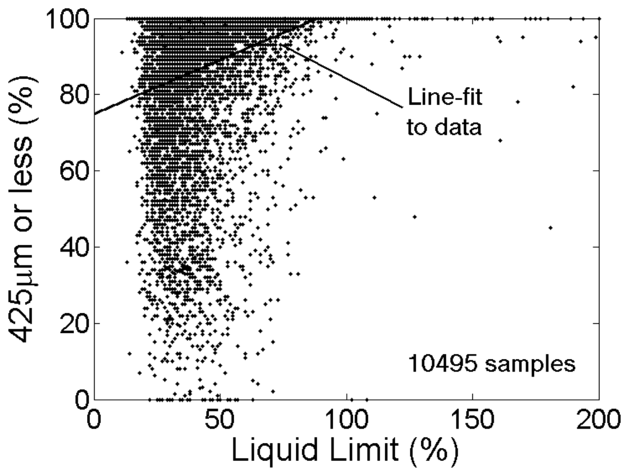

Figure 6 - The percentage of soil fines in the samples, versus their liquid limits.

A further aspect of BGS data that must be considered is whether the depths they represent are adequate for predicting soil effects on GPR. If limited to very shallow depths, such as samples at surface level, it would not be fully representative of soils likely to be present around the utility, and too great a depth would make the data less representative of superficial surface deposits. This has been investigated as shown in Figure 7, which considers the depth to the midpoint of each soil sequence that has liquid limit data associated with it.

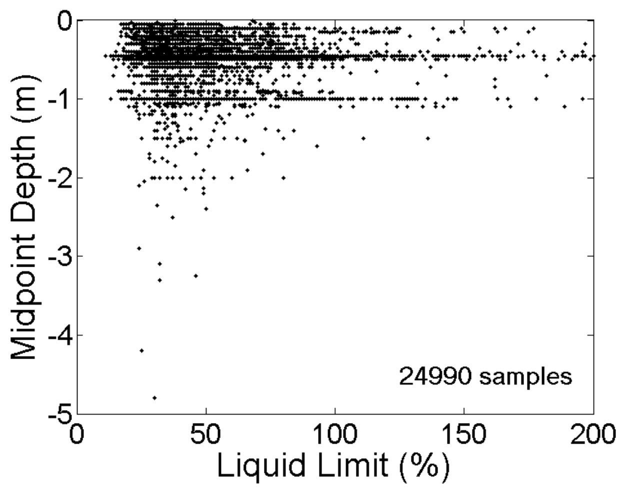

Figure 7 - The depth range covered by the samples, versus their liquid limit.

The figure shows that most liquid limit data relate to the first half metre of soil, but with considerable data also relating to the first metre of depth. As most utilities are buried within the first metre below ground level, and GPR will have difficulty seeing anything deeper than this in heavy clays, it is apparent that the depth ranges covered by the BGS databases are appropriate for most GPR utility location scenarios.

Another important consideration is the ground level elevation range within which data are available. From Figure 8, based on BGS data, it is apparent that the majority of liquid limit data relate to ground levels below 150m elevation. Given the large range of elevations that prevail within the UK, this may appear a limitation, but it must be remembered that the majority of population centres are located on low-lying ground closer to sea level, largely for historical reasons. However, full analysis of the BGS databases has yet to be undertaken, from which more precise details of data limitations, and hence future research needs, can be derived. Also, it must be remembered that the BGS data relate to UK soils: in other nations high liquid limit clays may exist at much higher elevations than are shown in Figure 8.

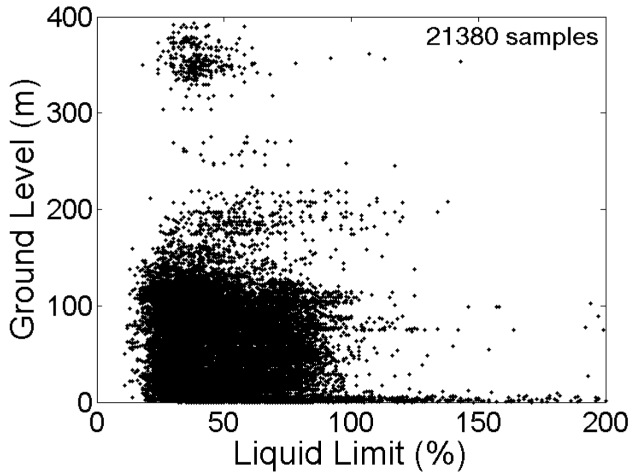

Figure 8 - The ground level at which the samples were taken, versus their liquid limit.

It is also interesting to note that relationships are expected between plastic and liquid limit data for individual soils. This fact is of particular use where plasticity data are incomplete, or where only the commonly used plasticity index (liquid minus plastic limit) is available. An important geotechnical relationship is based on the 'A-Line' which relates the liquid limit and plasticity index. As Figure 9 shows, BGS plasticity data exhibit a trend almost indistinguishable from the A-Line, which is a good indication of data quality in their databases. However, the A-Line is a general representation, and so does not discriminate between soils lying close to it and those showing significant departures. For this reason, it is apparent from Figure 9 that further work is required, providing relationships for a number of soil taxonomies, if predictions are to be more accurate than simple use of the A-Line. This would also involve further signal velocity testing for each identified taxonomy, as all of the soils in Figure 3 fall close to A-Line values.

There are obviously many more relationships inherent in the BGS datasets, and other databases, such as geophysical survey data held by the BGS, that could be used to provide additional data for prediction of soil data for GPR. However, it is hoped that the above discussion provides some insight into the wide geospatial and soil property distributions available from which to develop GPR suitability mapping. At first, at least in the UK, this will focus on major population centres, as this is where BGS soil data are largely focussed. However, in future, further data could be utilised, potentially by canvassing for more data donations by developers and even from inverted GPR data.

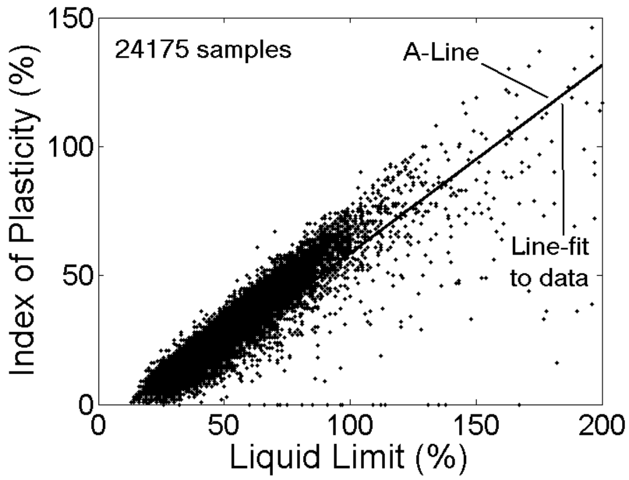

Figure 9 - Comparison of the samples to the A-Line.

Furthermore, other work is also being undertaken that provides invaluable information on the electromagnetic properties of soils, their impact on GPR signals and, therefore, their significance to GPR soil mapping. Dedicated measurements and numerical analyses, undertaken by the ORFEUS project, have shown a strong and reliable correlation between the early-time recorded amplitude behaviour of the GPR signal and the ground surface impedance (a property related to permittivity and magnetic permeability that determines the amplitude of reflected GPR signals). Also, the ORFEUS soils measurement programme has produced detailed information about changes in the electrical properties of soils *in situ*, in the first metre below the surface, when changing from a cool and wet season to a warm and dry season. For a commercially available GPR, velocity and attenuation profiles have been delivered and were compared with information taken from measurements on soil samples of 100m length, each from the surface to 1m depth. It was found that the electrical properties change by more than 100% within the first metre below surface, leading to strong vertical velocity gradients, and even in a relatively dry period grass roots can keep the near surface conditions wet resulting in a strong impedance contrast at the ground surface.

ORFEUS has also tested the ability of current GPR systems to detect the presence of buried pipes in three different test sites, one on a grass-covered anthropogenic sandy lane. The tests were done in two seasons, and concerned the detection of metallic and plastic pipes of two different diameters buried at different depths between 1.00m and 0.25 metre below the surface. The second set of tests was performed in the Gaz de

France Suez test site (in Paris) on pre-installed pipes, and the last tests were done under real-world conditions in several locations near the city of Brno, in the Czech Republic. These data will soon serve as a benchmark for improvements made with the newly developed ORFEUS project surface GPR system.

ORFEUS has also assessed soil quality, and the variability thereof, at the surface and in shallow depths in urban areas of Europe. Firstly, the natural variability was assessed of mostly Quaternary sediments forming the surface beds. Secondly, long time development of many European cities has resulted in the formation of very thick beds of heterogeneous anthropogenic layers, as illustrated in Figure 10. These are mostly composed of mixed materials of natural soil and debris, including crushed former construction material, as shown in Figure 11. These anthropogenic materials have different properties, and show different behaviour, compared to natural soils in response to electromagnetic and mechanical disturbances.

Figure 10 - Historic downtown of Brno, with blue marked areas of anthropogenic layers (courtesy of Geotest, a.s.).

Figure 11 - An example of anthropogenic layers formed of gravels, sands and loams at Oslavany Square near Brno, Czech Republic, where a water pipeline is laid (Photo courtesy of L. Svoboda).

The work of the ORFEUS project highlights the importance of further research to quantify the effects of such debris-affected soils on GPR signals, in comparison to the more natural local soils in which the debris is found. It may also, potentially, provide an initial data source to quantify the degree of geospatial variation in anthropogenic soil likely to be encountered in European cities.

From the above discussions it can be seen that the prediction and mapping of soil geophysical properties would involve a great deal of complex data requiring geospatial interpretation. In this regard, the work of BGS in visualising data three-dimensionally should also be noted, as the BGS has undertaken extensive investigation into the use of specialist software (GSI3D [18] - see http://en.wikipedia.org/wiki/GSI3D and Figure 12) together with BGS's in-house data visualisation suite. At present, this software is being developed for the visualisation of geological data, which in terms of surface geological deposits is highly relevant to GPR soil mapping as it allows greater understanding of the soil types and sequences prevalent at a survey site. Also, by viewing data within the GSI3D virtual reality window, it becomes a simple task remotely to assess morphological profiles that may impact on survey work and may give rise to local variations in soil water content (e.g. surface depressions).

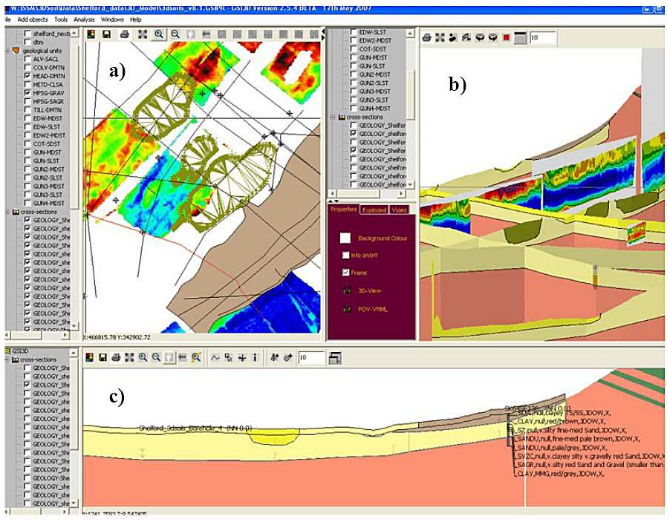

Figure 12 – An example of GSI3D use, illustrating simultaneous visualisation of plan, cross-sectional and 3D views of geological/geophysical data.

A further significant feature of this software, which may be utilised on less powerful computers than those used by BGS, is the ability to visualise simultaneously geophysical data, such as GPR plots, and geological data, all in a fully three-dimensional view. This is illustrated in Figure 13, in which GPR plots have been superimposed on geological data; it can be seen that the task of interpreting the GPR data, in terms of soil-soil and soil-rock horizons, is much simplified. While in itself this significantly aids GPR survey interpretation, the proposed work of MTU to incorporate utility location records into virtual reality interfaces will allow 3D visualisation to become an increasingly useful tool for GPR practitioners.

Figures 12 and 13 are the result of contributions to the BGS 3D Soils Project at Shelford, Nottinghamshire [19], in which integrated geophysical and geotechnical investigations were carried out in order to create 3D models of the shallow sub-surface [20].

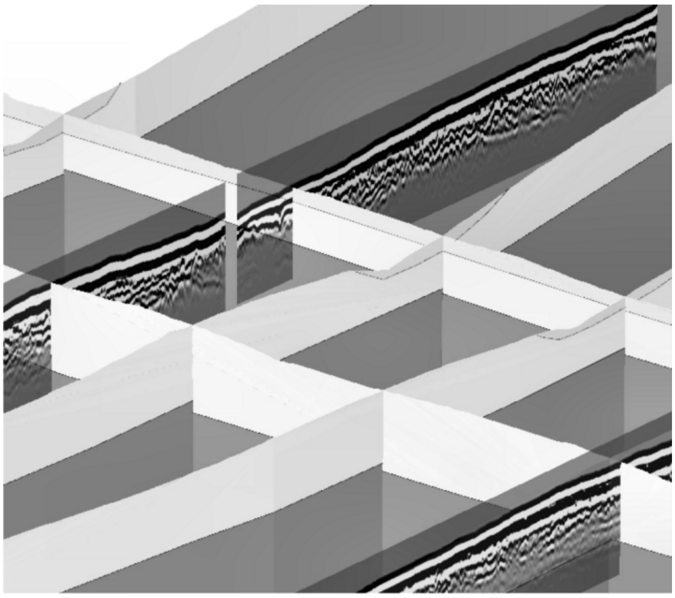

Figure 13 – Combined 3D visualisation of geological and GPR data in GSI3D.

IV. Discussion and Conclusions

Currently, GPR utility location operatives and organisations can often rely on having few, or no, data on the effects of prevailing soils on their surveys. Often, this means they will have to plan their work, and interpret their data, without a full understanding of potential signal velocities and levels of attenuation: hence they may have no data on the depth within which usable reflections will be received. To make matters worse, mapping GPR soil suitability using direct measurements would be prohibitively expensive and would be impracticable due to the need for large-scale intrusive excavations through hardened surfaces.

However, it is possible to estimate potential soil effects on GPR, as has been demonstrated in the United States [16]. Also, as has been discussed in this paper, it is possible to extend such methods, where data exist, to provide more detailed information, particularly for problematic soils such as heavy clays. By using existing geospatially indexed databases, such as those of BGS in the UK, it is already possible to begin formulating a prototype mapping system.

By encouraging greater donation of soil investigation data for these databases, particularly for urban developments where soil properties may have been significantly influenced by past human activity, it would also be possible to improve mapping resolution and quality. Potentially it could even be used as a template for the creation of suitable databases across Europe, or in any country where it is needed. Furthermore, by utilising soil electromagnetic testing methods, and geophysical/ geotechnical relationships, developed by such projects as MTU and ORFEUS, it would be possible to add targeted information for areas with poor coverage, or where necessary to characterise specific soils.

The most important conclusion that can be drawn from the above discussions, however, is that it is possible to develop methods of predicting, even mapping, the effects of soils on GPR signals without extensive, and prohibitively costly, direct electromagnetic measurement over wide geographical areas. While exact details of the potential accuracy is yet unknown, and must be determined, these data could provide significant advances in the planning and interpretation of GPR utility location surveys.

Finally, there can surely be many objections to the efficacy of predicting and mapping the impact of soils on GPR signals. Perhaps most notable is the impact of disturbed urban ground on potential accuracy, although even under those conditions such predictions would, at worst, still provide worst-case predictive data for velocity and attenuation, even if providing limited information on potential scattering of GPR signals by debris. However, it could similarly be argued that there is little efficacy in undertaking GPR utility location surveys with little or no information on soil effects, when extensive data currently exist, in an extendable form, that can be taken advantage of by the GPR community with relatively little effort.

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