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Mapping the Underworld - Enhancing Subsurface Utility Engineering Performance

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ABSTRACT

The location of buried utilities is becoming a major social and financial issue worldwide, largely due to the ever-growing underground infrastructure, the long history of its installation and the lack of accurate positioning records of existing services. Even when records are available, the term 'accurate' is blurred by the distinction between absolute (precise x, y, z coordinate values) and relative positioning, completeness of utility records and differing perspectives on appropriate measurement tolerances.

Additionally, large social and safety costs associated with disruption to construction works and traffic, caused by intrusive utility location excavations or unexpected utilities in excavations, require appropriate countermeasures that allow utilities to be located with confidence and precision. This led to the development of Subsurface Utility Engineering (SUE) as a process for combining civil engineering, geophysical prospecting, surveying and data management. This process incorporates minimally intrusive vacuum excavation for the "z" verification to produce a single package intended to meet the needs of stakeholders. However, no universally-agreed definition exists of stakeholder needs. Equally, no currently-available geophysical location technology can accurately locate all utilities.

This paper describes research into stakeholder needs, relating this to current SUE best practice. It then describes complementary UK research that aims to provide advances in the SUE process, via the Mapping the Underworld (MTU) project. MTU is researching the integration of multiple geophysical sensors into a single device able to detect all buried utilities without the need for proving excavations, together with positioning, data record integration and asset tagging technologies.

INTRODUCTION

Utility Location Problems

Poor utility location and management practices, during design, construction and maintenance, have the potential to increase property damage, injuries and even deaths. Due to the prevalence of utility works in highways, they additionally bring significant daily disruption to road users via extensions to construction contracts when unexpected utilities in excavations cause emergency utility diversions or, worse, repairs if they are damaged. This additional congestion, in delaying individuals and those on business, represents a very substantial "social cost", while the "environmental costs" of congestion are well researched. Therefore, utility management methods that do not adequately minimize these effects adversely impact on all three pillars of sustainability (economic, social and environmental). For a graphic illustration of this, one need look no further than to the July 2007 team main rupture, and similar past steam main incidents in New York City (1), which illustrate the potential for utilities to cause severe impacts to all three pillars, in those instances through death, injury, loss of business revenue, displacement of residents, asbestos contamination and

disruption of the highway network.

In the US, Subsurface Utility Engineering (2) should be used during the development of utility service projects that impact on highways, to minimise the risk of unexpected utility services being encountered. The traditional approach in the US was to notify one-call notification centers and/or utility companies, who would mark the ground indicating the approximate location of underground utilities prior to any excavation. However, in recent years, there has been some crossover since markings on the ground, performed by utility companies or their locators, have been surveyed and used for design purposes with serious potential consequences. Locators, hired by a utility company, typically provide information on one utility only and visit many sites each working day. Conversely, it takes much longer to perform a SUE investigation, because SUE providers may spend several days at one site to obtain reliable information on all existing utilities. Therefore, while SUE carries a heavier financial cost than simple site marking up, it also provides the full spectrum of utility location data required for managing not just the financial costs, but also the safety and social impacts.

A Common Problem - but for Whom?

A simple acid test of those people who suffer from a problem is to ask who would benefit if the problem were solved. Applying this test to utility location brings quickly the conclusion that construction operatives would suffer fewer incidences of death and injury than occur currently. Equally, clients and designers would be less concerned with the financial costs associated with delays due to the unexpected encountering of utilities during construction. However, extending this concept further, it is evident that all citizens would benefit, through such factors as reduced disruption due to highway works and reduced utility bills by companies avoiding the cost of unexpected utility diversions. When viewed from this perspective, it is apparent that the problems of accurate utility location are shared by everyone.

The Development of SUE

SUE developed in the US, in the early 1980s, because traditional methods of dealing with subsurface utilities were proving inadequate. It was common practice to design projects without consideration of utilities and to deal with them during construction, often after being located unexpectedly during construction. These frequent unexpected encounters with subsurface utilities resulted in unplanned utility relocations and delays. This was a costly and inefficient process, but was considered unavoidable because the locations of subsurface utilities, either from records or from the results of technology available at that time, were considered at best to be only a guess. It seemed possible that two technologies, air/vacuum excavation and surface geophysics, could be combined to gather data on the exact locations of subsurface utilities early in the development of projects. Accordingly, geophysical survey equipment was used to determine the presence of utilities, while air/vacuum excavation was used to confirm the findings and provide accurate positional data at discrete locations. In the late 1980s, SUE was used by various Departments of Transportation in the US as an addition to the then current designating and locating activities, most importantly surveying and data management, sealing deliverables and professional liability insurance.

In the 1990s, more US states began to use SUE and more providers emerged as SUE evolved as a process involving managing certain risks associated with utility coordination and utility mapping at appropriate levels, ranging from information on existing utility records to the use of surface geophysical techniques combined with minimally-intrusive local proving excavations at critical points. In addition, the SUE process includes features such as utility conflict analysis, utility relocation design and coordination, utility condition assessment, and communication of utility data to concerned parties. However, it is important to recognise that SUE must be tailored to individual projects, and can be as detailed as deemed necessary to minimize the risk for individual projects. Since then the use of SUE has spread throughout North America and other parts of the world, but is still not commonly used in the UK.

Common International Goals

Of the several shared problems facing civil engineers internationally, traffic congestion is one of the most severe, while the deteriorating condition of buried utilities is growing in importance in the public's consciousness. The impact of utility works on traffic congestion is well-established in society's mind, emphasizing the concomitant importance of accurately locating underground utilities. To illustrate this point, recent research suggests that the UK utility industry's annual direct construction costs associated with street works are currently around £1.5 billion, with third party damage costs of the order of £150 million, while the social costs of street works (delays to road users; environmental damage; disruption to businesses; air pollution; etc.) may be as high as £5.5 billion a year (3). Furthermore, it has been estimated that between 10% and 20% of utility work, in the UK, accounts for as much as 80% of the social costs. SUE addresses these problems via its location activities, using the data proactively to aid planning of construction works. By taking the opportunity to determine and record the condition of buried assets during location surveys, it can combine this information with positional data to assist in the proper management of underground infrastructure. Developing such thinking, this paper seeks to explore the opportunities for SUE development and introduces a UK project (Mapping the Underworld) that aims to achieve these same goals without surface excavation.

When SUE is deployed fully and accurately it can markedly reduce the costs of construction through accurate planning and mitigation of construction risks. For example, case studies at

Purdue University and the University of Toronto showed that a total of \$4.62 and \$3.41, respectively, were saved in avoided costs for every \$1.00 spent on SUE (4, 5). These findings are hardly unexpected to Geotechnical Engineers, who have for many years advocated adequate, and appropriate, spending on site and ground investigation, in order to avoid unnecessary construction costs. This is, in effect, an intelligent form of specific site investigation and long-term data capture. In this light, the paper aims to define better the target of utility locating operations and show how intelligent study of the ground can be used to advantage in improving the processes via, what are in essence, ground investigation techniques. The paper ultimately aims to demonstrate that enhancement of the SUE process is a common international goal and will deliver major common benefits.

ADDRESSING STAKEHOLDERS' NEEDS

MTU Survey of Stakeholders' Requirements

At first sight SUE can be considered a technical response to a technical problem. However, the implications of poor utility location (e.g. injury, costs, disruption, etc.) only exist because they directly affect everyone involved in the process, including road users, utility providers, city planners, contractors, and many others (i.e. the stakeholders). Therefore, any problems, or solutions, associated with SUE must be defined in a stakeholdered manner. While the MTU founders based their work around knowledge of their industry partners' needs, wider consultation was required to define and quantify the operating parameters of the project's outcomes.

To achieve this, MTU holds workshops (6) and recently ran a questionnaire, gaining >80 responses from a wide range of utility management, operations and construction stakeholders; responses from the first 70 are detailed below. Both have provided a unique insight into the needs of stakeholders and helped guide the research toward appropriate outcomes (7). For example, stakeholders' views of factors central to utility location are illustrated in Figure 1 which, although based on subjective views, allows important issues to be ranked in order of priority. The importance of locating critical services (defined as those causing significant safety and cost issues if damaged) was given the highest priority. This immediately illustrates the necessity of SUE as a location process, and MTU as an improvement to it, as it provides a means of managing the risks associated with utility location in a manner that cannot be achieved by simple use of utility records.

Of slightly lower priority are the issues of accurate detection and understanding potential errors. That both are given equal ranking is not surprising as complete accuracy cannot be achieved unless error potentials are understood and properly managed. However, as one stakeholder commented: "There are many types of utility detection equipment available in the market. No information is available about their performance and accuracy." Therefore, the issue of understanding potential errors is not only a matter of achieving the greatest accuracy possible with available equipment, but also a matter of understanding the operational limitations of the equipment.

It is also evident that accurate depth assessment, while still considered important, is given the lowest priority, presumably following the argument that depth information is of reduced importance without the plan location. A further consideration is the depth over which SUE should provide location data during 'normal' and 'rarer' surveys. Figure 2a indicates that UK stakeholders require location of utilities from surface level to deeper than 5m, but with a maximum depth of 3m being adequate for most scenarios. These depths might be expected to increase if North American stakeholders were questioned, since the UK is largely free from frost depth penetration. FIGURE 2 Stakeholder (a) Depth and (b) Accuracy Requirements

The tolerances within which stakeholders expect SUE to detect utilities, both in plan and depth, was questioned. Figure 2b shows that, almost without exception, stakeholders require accuracies to be no worse than $\pm 300\text{mm}$. However, if the majority of UK stakeholders are to be satisfied, tolerances of $\pm 100\text{mm}$ are required and, preferably, should be better than $\pm 50\text{mm}$ (if at least 90% of stakeholders are to be satisfied), which is a much stricter requirement than the more forgiving tolerances sometimes applied to SUE.

As well as defining operational requirements, stakeholder engagement has also given an indication of the frustration stakeholders feel toward utility location issues, including the accuracy of mapping which one person described as "...not reliable to any degree", while another stated that accurate mapping would "...help to reduce the level of uncertainty associated with sub-surface workings." Stakeholders have also shown wide concern over current knowledge of equipment limitations and the safety issues of utility location, with one stakeholder commenting "... understanding the operational limitations on any detection equipment and the findings are critical to safety."

A final aspect of stakeholder comments central to SUE, and its improvement, is the need to remember that perceived benefits should be seen by all stakeholders, rather than just those engaged in the technical aspects. In this regard, many comments were received concerning the need for clear and understandable data communication, for example "It is not only important to obtain the correct information with regards to location and depth of utilities, but to present that information in a clear and user friendly format." Furthermore, the risks of ignoring the needs of all SUE stakeholders were nicely summarized by: "Accuracy requirements are job specific and if a mapping contractor cannot provide the accuracy I need there is no point in using him."

Addressing the Issues

The problems of inaccurate utility location, which are reflected worldwide, were highlighted at the first UK Engineering and Physical Sciences Research Council (EPSRC) Engineering Programme Network in Trenchless Technology (NETTWORK) workshop. Despite previous research into other areas of geophysical location equipment use (e.g. unexploded ordnance detection), the requirement for a multi-sensor tool specifically for locating buried utilities was subsequently identified (8) due to significant application-specific needs, along with parallel research projects covering mapping, data/knowledge management and asset tagging. An EPSRC IDEAS Factory resulted in the formation of MTU as a multi-university research team incorporating industry partners (www.mappingtheunderworld.ac.uk).

A Common Goal

SUE and MTU are predicated on providing accurate positioning, planning and data management for all underground infrastructures, for which an understanding of relative accuracy and residual risk is fundamental. To achieve the highest quality, SUE practice in North America relies on non-destructive excavation techniques, such as vacuum excavation. In contrast, MTU aims to develop a multi-sensor location tool providing the location of all utilities, to a high level of accuracy and consistency throughout the normal depth range of utility installations, without ground disturbance, thereby providing a potential enhancement to SUE. We acknowledge this to be an ambitious goal, and one that is far from possible using current technologies in isolation (9). However, the results of

the current MTU feasibility studies indicate that, with intelligent use of soil data and fusion of the outputs of different devices, the goal is not unrealistic if sufficient resource is devoted to the research. An important aspect of MTU is the involvement of all relevant industry sectors (utility providers, academics, local authorities, consulting engineers, and contractors); their full endorsement of the research aims and willingness to collaborate provides confidence in both meeting the aims and subsequent application of the results. Conversely it has also been demonstrated, through comments received from stakeholders, that failure to ensure that SUE consistently meets these needs could result in it being considered an ineffective solution to the difficulties of locating buried utilities, and its rejection. It is, therefore, evident that if the important improvements to industry practice made by SUE are to be universally realised, then the current research to keep up with stakeholders' increasingly-demanding expectations is essential.

BEST PRACTICE IN SUBSURFACE UTILITY ENGINEERING

Planning Ahead

SUE has evolved in the US over recent decades. It is a highly efficient process incorporating civil engineering, surface geophysics, surveying and mapping, non-destructive vacuum excavation, and asset management technologies to identify and classify quality levels of existing subsurface utility data, as well as to map the locations of the underground utilities (10). SUE has become a routine requirement on many highway projects and is strongly advocated by the US Department of Transportation's Federal Highway Administration (11). SUE is recognized in a national standard developed by the American Society of Civil Engineers (2) and the cost-savings studies at Purdue University (4) and University of Toronto (5, 12) provide evidence of its efficacy in minimizing costs and risk (13).

The ASCE standard closely follows concepts already in place in the SUE profession. Many highway agencies, and/or their design consultants, use SUE routinely in the early development of projects by employing the services of SUE consultants to identify the quality of subsurface utility information needed for highway plans, and to acquire and manage that level of information during the development of projects. This enables designers to prepare plans with thorough and comprehensive knowledge of the exact locations of underground utilities, and enables excavators to avoid damaging underground assets (14).

Major SUE activities are scope of work, designating, locating, data management, and conflict analysis. Scope of work is the process of developing a written project-specific work plan package that consists of scope of work, levels of service versus risk allocation, project schedule and desired project delivery method. The SUE work plan package is agreed upon by the SUE provider and the client, describing the SUE work to be performed. Designating is the process of using a surface geophysical method or methods to interpret the presence of a subsurface utility and mark its approximate horizontal position on the ground surface or on above-ground surface markers. Locating is the process of exposing and recording the precise vertical and horizontal location and providing utility size and configuration of a utility. Data Management is the process of surveying designating and locating information to project control and transferring it into the client's CAD system, GIS files, or project plans. Conflict Analysis is the engineering process of using a conflict matrix to evaluate and compare depicted designating information with proposed plans (highway, bridge, drainage, and other) in order to inform all stakeholders of potential conflicts, potential resolutions (including avoidance of utility relocations where possible) and costs to cure. Although there is more to SUE than this, these are the basic elements (15).

Even though SUE is widely used in the US, obstacles such as funding, thorough understanding of application vs. benefit and old school reluctance to change is preventing it from being used to the extent that it should be. Stakeholders recognize needs for accurate and comprehensive subsurface utility information but many don't want to pay for it, don't fully understand it, and/or don't have confidence that it will give them what they need. Therefore, there remains a need in the US to continually educate stakeholders and to continually provide highquality information.

Choosing Location Technologies

Current best practice for locating subsurface utilities involves the use of many pieces of geophysical prospecting equipment, including pipe and cable locators, terrain conductivity methods, resistivity measurements, ground-penetrating radar, and 3D radar tomography (16). In addition, there is a diverse range of soil conditions in the US that affect geophysical signals. This requires operators to have a wide knowledge of the soils' properties in order to take full advantage of the capabilities of locating equipment. Possibly even more important than the equipment is the operator's knowledge of equipment capabilities and ability to understand information portrayed on equipment monitors; this takes much training and experience, and there is much room for error. Hence, there is continually a need for the development of better, more user-friendly equipment.

Ensuring Accuracy and Confidence

Use of SUE in the US by responsible providers has resulted in the provision of consistently accurate information. However, as with any emerging discipline there are growing pains as processes are formed and improved, some providers do better work than others and in the earlier days of SUE some providers, mistakenly believing they understood the process when they didn't, provided inferior information. This often caused clients to believe that SUE provided no better information than they were currently using. While the advent of the ASCE standard (2), which has become the standard of care in the US for obtaining existing subsurface utility data, has helped in establishing best practices, residual concerns exist over the use of these best practices by some practitioners, indicating a potential need for improved training and accreditation.

Thus, even though SUE is considered by many to be adequate at present, the need remains for even better, more reliable, and more cost-efficient methods to manage problems associated with inadequate utility records, which in turn requires more research into improved location techniques and operational standards. Until recently the US had initiated limited research that could be considered comparable to the UK's MTU research. However, early in 2007 the Strategic Highway Research Program 2 (SHRP 2), administered by the Transportation Research Board, funded and advertised a contract that was awarded to Louisiana Tech University entitled: "Encouraging Innovation in Locating and Characterizing Underground Utilities." The goals of this research are to identify current problems in locating and characterizing underground utilities, to identify potential new methods and technologies, and to prioritize and recommend promising methods or best practices for future development (<http://www.trb.org/shrp2/>).

CURRENT ADVANCES IN SUBSURFACE UTILITY ENGINEERING

The MTU Approach

It is clear from the above that a number of issues require addressing, including optimized multiple sensors, improved knowledge of soil geophysical properties, improved location recording and mapping, improved visibility of utilities to location equipment, and integration of these factors into a single, coherent, technology. These factors are central to the research approach being adopted by MTU (6) and are intended to radically improve the data provided by geophysical technologies in order that the location problems associated with variations in utility burial depths and congestion of the underground space can be addressed. However, it should be noted that while this paper details the new and improved sensors being developed by MTU, current technologies are also available that may provide additional data on individual utilities - e.g. cable avoidance tools - and in locations where access is limited, where radio sondes and other such technologies may be appropriate. Therefore, where not superseded by the MTU research, existing technologies that may complement the multi-sensor device will also be considered for inclusion in it.

Multi-Sensor Development

At present, geophysical location surveys are based around sequential deployment of GPR, acoustic and radiated magnetic field technologies. To expand on these options, to cope with all soil and utility types encountered, MTU is researching four new/adapted techniques. The first is a novel GPR configuration for use within pipes and other underground conduits (17). However, in contrast to other in-pipe systems, this research concentrates on inpipe transmitters directly coupled to surface receivers. This reduces signal loss and removes the need for reflections from utilities to be detected at the surface (as utilities will appear as shadows in the received signals).

GPR is limited by very high signal losses associated with conductive soils (e.g. clays). However, this very limitation is being turned into a new location technique in the form of very low frequency electric fields (18). As illustrated in Figure 3, obstructions of low conductivity (e.g. plastic pipes) cause bunching of field lines, in turn causing variations in the surface-measured electric field. This technique has potential to detect the small, nonmetallic, services that cause great difficulty for other location techniques. FIGURE 3 Low Frequency Current Flow in the Ground

Acoustic utility location equipment is already in use, but is limited by difficulties in detecting vibrations through hard surfaces and problems ensuring adequate radiation of vibrations into the surrounding ground. Possible methods exist for mitigating these problems (19), including different excitation types to maximize the energy transmitted into the pipe system and the effect of selecting optimized frequencies or frequency bands to suit specific situations. As with all geophysical systems, acoustic devices can be adversely affected by interference, in this context vibrations caused by adjacent traffic and other activities. While this will be partially mitigated by the need to

reduce traffic movements while traversing the investigation area with the multi-sensor device, MTU is also developing the system to take advantage of the measurement of vibration phase as a means of detection. In combination with undertaking measurements over a wide range of signal frequencies, it is intended that the effects of unwanted vibrations will then be further mitigated.

MTU is also investigating magnetic fields produced by electrical current flow in cables. Current line tracing equipment detects these magnetic fields, but only provides data on the presence of a utility through which current flows. By concentrating on measuring variations in the magnetic fields caused by nearby utilities, i.e. those occupying the adjacent underground space to the cables that are producing the magnetic fields, non-conducting services can be detected (6).
Assisting Future Location

For GPR, where the strength of a reflected signal is largely dependent on soil conditions, the loss of signal strength with depth can be particularly high in wet soils. Therefore, GPR can sometimes be ineffective in detecting utilities at depths as shallow as 0.5m. Improved visibility of the utility would improve on this problem, a concept being advanced by MTU based on the resonant properties of circuits containing capacitive and inductive elements, which cause reflected signals to have a greater power level than the incident signals (20). The tags being produced are passive (i.e. require no built-in power supply) and small enough to be easily attached to new or repaired utilities.

They also have the advantages of partially reduced signal loss, a distinctive reflection and the potential for coded information (e.g. utility type, age, material, depth) to be provided in the reflected signal.

Improving Utility Recording and Mapping

Central to SUE is the problem of inaccurate or incomplete utility records. Several features exacerbate this problem, including the need to obtain data separately for each utility type, the lack of common base maps and differing methods used to record utilities during installation. MTU is addressing the integration of all utility records, using a single base map by providing a novel portal to seamlessly integrate all utility company databases, while allowing companies to maintain responsibility for their own records.

However, even when the location of a utility has been recorded, the location information will often be based on relative coordinates. This is a particular problem with older records, as features used to reference the utility location will often have been removed or altered. An obvious solution is absolute positioning using Global Positioning Systems (GPS). However, in urban areas with closely-spaced tall buildings, GPS suffers severe difficulties accessing satellite signals (21). MTU is addressing this through system integration (e.g. GPS, GLONASS and Galileo) to increase the number of visible satellites, and investigations into the use of pseudolites (i.e. accurately-located ground-based transmitters), with the aim of achieving GPS location accuracies in the region of $\pm 10\text{mm}$, even in 'urban canyons'.

Understanding Equipment Limitations

A current limitation of location equipment is that performance characteristics are not defined for the full set of soil and utility type scenarios. This is significant as current location technologies are highly dependent on the effects of soil in terms of signal velocity, signal strength losses and the minimum detectable utility size. Therefore, without detailed knowledge of these effects, equipment choice may be largely ad hoc. It is currently proposed that this be addressed via creation of a state-of-the-art test facility (which, while being UK-based, could be used as a template for similar sites world-wide) incorporating a wide range of utilities and different surface and sub-soil types. The underground utility infrastructure will be surveyed to sub-centimeter accuracy using GPS and the site will incorporate monitoring of the geotechnical and geophysical soil states. As well as being used for equipment testing, the site will also provide training and accreditation functions, thereby ensuring consistently high standards among SUE practitioners.

To address the need for clear communication, an accuracy assessment system has been formulated from the questionnaire data, allowing the accuracy of location equipment to be judged against the percentage of stakeholders satisfied by that accuracy (22). By formulating the assessment system in this way, the spatial data are weighted toward the needs of stakeholders as a measure of equipment accuracy. Furthermore, through testing equipment over a wide range of utility types, location devices can be rated for use in a number of survey scenarios where stakeholders may have greater or lesser expectations of location accuracy than can be accounted for by a single average score. This allows the system to avoid indiscriminately branding a device as being inappropriate for utility location when it may provide specific benefits to stakeholders.

Tuning into the Soil

Soil is the common factor in utility location surveys. Detailed knowledge of its effects on geophysical signals is required for adequate analysis of location survey data and for selection of the most appropriate location technology (23). This required knowledge of soil electromagnetic properties can be derived in two ways: where access to the soil is possible, direct measurement of electromagnetic properties can be made; where this is not achievable, it would be advantageous to predict the impact of soils on signals from some form of geographically mapped geophysical properties.

The field testing aspect is being based around Time Domain Reflectometry (TDR, 24), which is

widely used for electromagnetic soil characterization. The technique is being developed beyond current 'norms' to include broadband frequency domain measurement over the full range of frequencies generally used for utility location GPR (i.e. 100MHz to 1GHz). This is necessary due to a property of soil known as dispersion, which causes the electromagnetic properties of a soil to vary significantly within the GPR bandwidth, as illustrated in Figure 4a. FIGURE 4 Soil EM Properties Versus (a) Frequency and (b) Water Content

Undertaking a mapping exercise, using measured electromagnetic data over large areas, however would be an impracticable proposition, leading MTU to consider factors common to both electromagnetic signal propagation and geotechnical properties, from which soil electromagnetic properties can be predicted and mapped. This work is based on two features of dispersion exhibited in Figure 4a: variations in electromagnetic properties over the lower GPR frequencies, and a leveling off of these variations at higher frequencies. These features are dependent on the properties of two types of water - that tightly bound to soil mineral particles and that relatively unaffected by the presence of soil particles. The proportions of these two types of water are determined by the specific surface area of the soil and less dispersion occurs in the soil at the liquid limit, due to a significantly lower specific surface area. If the proportion of the bound and free water can be determined, this dispersion can be modeled using known formulae (25). Fortunately, the higher frequency electromagnetic properties of dispersive wet clays are highly correlated to water content (Figure 4b), as identified by Wensink (26) whose model for electromagnetic properties at 1GHz is shown for comparison. The predictability of the higher-frequency free water properties allows the determination of bound and free water proportions in a clay, provided that the water content and geotechnical properties are known, providing a basis for prediction and mapping.

Although this work is currently focusing on GPR frequency electromagnetic properties, work is also ongoing to extend the methodology to include low-frequency electric field and acoustic soil properties. It is intended that this will include use of water content estimations, derived from the GPR sensors, as a basis for predictions based on laboratory soil testing and mapping data, in a similar manner to that described above.

Data Integration - The Big Leap Forward

A significant source of complexity in SUE is the volume of data that must be considered (e.g. numerous utility records, different types of geophysical data, etc.); when the MTU work is included, this complexity will increase. Consequently, MTU's core philosophy is that individual research developments will not provide standalone equipment, but will be integrated into a single location technology. This has several benefits, most notably the possibility of processing multiple data sets in parallel to maximize the level of detail in the geophysical survey data and allow field- and office-based visualization of the combined dataset, including enhancement through use of virtual- and augmented-reality equipment. This provides significant benefits in terms of data interpretation accuracy and makes the data more accessible to less technically-literate stakeholders. The most significant challenge associated with achieving this aim will, therefore, not be the improvement of existing signal processing methodologies for each sensor type (each already benefitting from a wide range of data-specific signal processing research), but will instead be the development of a means of integrating the processed data from each sensor into a coherent representation of the underground space, in a manner that is specifically designed to provide enhanced utility detection.

CONCLUSIONS

Potentially the most important conclusion of this paper is that stakeholders need a safe, minimally disruptive and cost-efficient way to manage the difficulties associated with inadequate utility records. While this is largely addressed by the high degree of sophistication to which SUE has developed in the US, it is apparent that research into improved location techniques, and agreed best practice standards, is required for SUE to meet the full requirements of the stakeholders who depend on it for their safety, and social, environmental and financial wellbeing. Although a UK-based project, MTU is addressing these central issues in a manner that is compatible with SUE use in other countries. This fact is not coincidental, as it has also been demonstrated that achieving the highest possible levels of technological achievement in SUE is a common goal.

It can also be concluded that the diverse range of soil conditions encountered in SUE requires an equally wide knowledge of the properties of soils, preferably coupled to techniques such as prediction methodologies and geospatial mapping, that can arm SUE practitioners with the tools they need to take full advantage of location equipment. Equally important is the conclusion that the strengths and limitations of current equipment, in terms of their operational limitations over a diverse range of utility and soil types, need to be documented to allow informed equipment choices. Furthermore, these issues highlight that a single geophysical technology is inappropriate for current research work and that a combination of sensor types is required, in parallel with integrated visualization of combined data sets, if SUE is to advance past its current level of sophistication.

Finally, the fact that any improvement to SUE needs to be stakeholder-led brings with it one other conclusion, this being that research into improved utility location is not a standalone concept.

Instead, its success relies on a process of integrating improvements into the current knowledge database built by stakeholders over the lifetime within which SUE has developed. As one stakeholder commented, "There is a vast wealth of experience and knowledge in the industry which can be put to good use by the research teams. It is important that this is taken to full advantage." Therefore, future progression of SUE relies on collaboration based on knowledge sharing between interested parties, as illustrated by the multi-national nature of this paper.

ABBREVIATIONS USED

MTU - Mapping the Underworld.
SUE - Subsurface Utility Engineering.
CAD - Computer Aided Design.
GIS - Geographical Information System.
TDR - Time Domain Reflectometry.
GPR - Ground Penetrating Radar.
GPS - Global Positioning System.

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The American Society of Civil Engineers (ASCE) has just released a new publication entitled Standard Guidelines for the Collection and Depiction of Existing Subsurface Utility Data. This document was reviewed and approved nationally through the ASCE consensus process. The document is important to all state and local transportation departments, including the Georgia Department of Transportation (DOT), because the justice system holds such standards in high regard, and courts and lawyers use them to assist both in defining a professional standard of care and in placing blame.

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