Pipeline Engineering in the Ground: the Impact of Ground Conditions on Pipeline Condition and Maintenance Operations

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ABSTRACT

The ground in which utility service pipelines are buried inevitably controls, to a large degree, the structural performance and progressive deterioration of the pipelines themselves. In a parallel programme of research to the UK Mapping the Underworld (MTU) project, a study of the fundamental properties of the ground, and how they change with the seasons and local physical and chemical contexts, is being conducted at the University of Birmingham, UK. While the results of this study feed into both the operational protocols for the MTU multi-sensor location device and the associated knowledge based system (KBS) that is being created to aid its deployment (both topics being the subjects of separate papers to this conference), the suite of complementary research projects on the ground and its properties provide valuable insights to the pipeline engineer. Geophysics is being used by the research team to explore the state of the ground with the aim of highlighting areas of concern for the structural health of pipelines buried in the ground. Studies of cast iron pipeline corrosion mechanisms have focussed on the changes that the reaction products cause to the surrounding soils, with a particular emphasis on clay soils, and one interesting finding is that these clay-iron reaction products can make the pipelines ‘invisible’ to standard geophysical location devices. Moreover there are other features in the ground that are being targeted (voids, ground wetting and softening due to leakage, ground weakening due to progressive erosion), and these features effectively make the ground more or less ‘visible’ to geophysical technologies. Alongside this work, bespoke tests have been developed for use on site to ‘calibrate’ the geophysics, thereby enhancing the signatures of the features. This paper introduces these parallel research projects and draws out the important findings for pipeline engineers charged with establishing the condition of existing buried assets.

INTRODUCTION

The Mapping the Underworld (MTU) initiative aims to research and develop the tools required to facilitate the wider adoption of trenchless technology, as opposed to open
cut methods, and sustainable working practices, when undertaking streetworks associated with buried utilities (Royal et al., 2010; Royal et al., submitted). One factor limiting the use of trenchless technologies that excavate or displace the ground (horizontal directional drilling, pipe bursting, etc.) is the inability to routinely locate all buried utilities in all but the simplest of soil conditions and utilities layouts using remote sensing technologies. Therefore, the current phase of the MTU project is researching and developing a multi-sensor platform that can be deployed to locate all utilities buried below the carriageway. Rather than deploy the multi-sensor device in isolation, the philosophy of the research project is to utilise as much information about the site as possible before and during the survey. Utility records will provide a prompt to what can be expected on site, and this information will be fused with the sensor data to produce a probability map for the utility locations on the site. Furthermore, information on the ground will be incorporated into a knowledge based system (KBS) that will help the surveyor predict the impact of the ground conditions on the performance of the sensing technologies deployed on the multi-sensor platform. The research and development of the KBS, and research into the relationship between the geotechnical properties and the geophysical properties of various ground conditions, are central to the MTU Multi-Sensor Platform project and the initial outcomes of these research initiatives highlighted the importance of the ground on the potential performance of various geophysical sensing technologies. Therefore a number of discrete research project have emanated from this work at the University of Birmingham that investigate various aspects of soil behaviour that can affect pipelines directly or influence the efficacy of the geophysical detection of the utilities. This paper introduces the aims of these projects and summarises the progress made to date.

CHANGING ELECTRICAL PROPERTIES OF VARIOUS SOILS WITH THE SEASONS

Shallow geophysical techniques such as Ground Penetrating Radar (GPR) are strongly affected by the type and condition of the ground. Soils are generally considered non-magnetic materials hence the permittivity and conductivity are the two most important parameters that influence the signal velocity and attenuation. The water content of the soil affects both parameters by reducing the signal velocity (high permittivity) and by limiting the signal penetration depth (conductivity). Conductivity increases with increasing water content and with the amount of salt and clay contents, therefore GPR applications in such soils are limited (Jol, 2009). Research is being conducted to investigate how the electrical properties of various soils change with weather conditions over time, and ultimately how this affects GPR techniques. The research involves the use of Time-Domain Reflectometry (TDR) monitoring stations in the field. The experimental data will also be used to validate existing models that predict geophysical properties based on a limited number of
geotechnical parameters (i.e. water content, particle size distribution) of the soil (Mironov et al., 2009).

TDR is a well-established technique used to determine the permittivity and conductivity of soils (Robinson et al., 2003). A pulsed signal is sent along a transmission line consisting of a coaxial cable and a multi-rod probe embedded in the soil. From the time taken by the signal to travel through the sensor and be reflected back it is possible to measure the permittivity of the material surrounding the rods. Figures 1 and 2 show examples of TDR waveforms used to calculate the soil permittivity and conductivity respectively. The numbers depicting the ‘data points’ on the abscissa correspond to time. The reflections identified by crossing tangents in Figure 1 are used to determine the velocity of the signal along the sensor that in turn gives the permittivity of the material according to Equation 1:

$$\varepsilon = \left(\frac{c}{v}\right)^2$$

where \(\varepsilon\) is the permittivity, \(c\) the speed of light in free space and \(v\) is the actual velocity of the signal. The soil permittivity is strongly related to the volumetric water content (Topp et al., 1980) therefore the TDR is mainly used in soil science as a tool to measure the ‘soil moisture’. The ability of measuring both permittivity and conductivity and the possibility of multiplexing (Baker and Allmaras, 1990) makes the TDR a versatile geophysical method that can be used in field monitoring stations.

![Figure 1. Examples of TDR waveforms used (left) to measure the permittivity of the soil and (right) to determine the conductivity of the soil.](image)

The TDR monitoring station, developed specifically for the project, consists of an array of TDR probes buried at different depths down to approximately 1 m. Data are collected on a regular basis and compared to weather station data. Figure 2 illustrates results obtained from a TDR probe at a depth of 0.35 m. This site consists of about 0.3 m of topsoil overlying a sandy subsoil with a surface covering of grass. At the beginning of October 2010 two important rainfall events occurred, with a cumulative rainfall of 25.8 mm falling in 19 hours on the 1st of October and 16.6 mm of rain falling...
in 10 hours on the 3rd of October. The first infiltration of water caused the permittivity to increase abruptly by about 3 units, yet the corresponding conductivity did not increase as significantly. At a depth of 0.35 m the soil at this site is a very gravelly sand that does not retain much water, resulting in generally low values of permittivity (6 - 9). Sand particles also have a small surface area that, combined with the small amount of retained water, explains the low conductivity values (2 - 3 mS m$^{-1}$).

The permittivity and conductivity readings (Figure 2) prior to the rainfall events, i.e. baseline readings, provide an indication of the precision of the TDR system. The corresponding standard deviations for the permittivity and conductivity readings are 0.033 and 0.129 respectively. This shows that the TDR is precise enough to give useful information on the soil conditions, and variability with time. Long-term monitoring will give information on the daily and seasonal variability in the soil’s geophysical properties.

Additional soils are being investigated, using additional TDR monitoring stations, and it is hoped with the additional data from these sites a better understanding of changes in both permittivity and conductivity with season can be obtained.

![Figure 1](image)

**Figure 1.** Permittivity (left) and conductivity (right) response at a depth of 0.35 m with time for recorded rainfall measurements.

**ASSESSING THE CONDITION OF BURIED UTILITIES USING GPR**

GPR has been used to detect structural defects, such as voids and cavities in road pavements, slabs and bridge decks (Koo & Ariratnam, 2006), but has not been used to assess the condition of buried pipes. If GPR could successfully be used to assess the degree of deterioration of underground pipes then it could become an important technique for asset management.

The basic concept of the GPR technique is based on a reflection technique which uses high frequency electromagnetic waves to acquire the subsurface information. The information on the subsurface structures can then be examined using the combined
image of reflected signal traces (Saarenketo & Roimela, 1998). A laboratory test facility, consisting of a box of dimensions 2.4m (length) x 2.4m (width) x 1.2m (height) constructed from structural insulated (timber) panel material, has been developed for this investigation (Figure 3). The size of the box was determined as the minimum requirement for the commercially available GPR unit based on beam width antenna calculations so as to avoid signal reflection from the edges or base of the box and to ensure the complete shape of the hyperbolic trace from the targets to be captured. The tests involve burying 0.2m diameter plastic pipes in the box (Figure 3). One of these pipes is in an undamaged and the other has a defect (i.e. break or hole), i.e. it is a damaged pipe.

The material in which the pipes were buried in the tests was a uniform coarse-grained sand (0.6 mm to 2.0 mm). This is a material that could be placed in the box consistently at 6% moisture content, i.e. there was minimal variation in density across the box and also between different tests. In addition, it is a material that minimizes signal attenuation, i.e. it provides a material that is relatively ‘easy’ for GPR signals to penetrate. This sand was compacted in layers to provide a uniform density throughout the box. The relative dielectric permittivity of the sand was determined as $\varepsilon_r = 2.72$ using TDR. From this result, the velocity of the signal was calculated as $v=180$ mm/ns for use in the analysis of the GPR data. A 0.1 m spaced GPR survey grid was used in the experiments, which produced 15 traverses, both in the direction of the pipes and perpendicular to the pipes. Data analysis is based on the signal contrast between the two types of pipe (damaged and undamaged) by using advanced interpretation (using a Matlab programming) to differentiate the signal amplitude between the different pipes using a Mean Square Error (MSE) method. The analyses have concentrated on the amplitude changes of a particular area of the GPR data obtained from the undamaged and damaged pipes (Figure 4).

15 GPR images relating to the crossing points on the survey grid along the damaged pipe (position 8 is where the break in the pipe occurs in this example) are presented in
Figure 4 along with the MSE. It is possible to quantify the signal amplitude changes between the undamaged and the damaged pipe section. Using the analysis techniques developed in this research and the preliminary test conditions utilised, i.e. where known damage has been incorporated into pipes under ‘ideal’ ground conditions, it appears that slight differences in the GPR signal related to these damaged regions can be ‘observed’ relative to undamaged regions on the pipe. However, it is appreciated that further refinement and testing under a broader range of ground and pipe conditions is still required. That said, whilst the testing undertaken may represent simple conditions, as is befitting preliminary research in this field, encouragement is drawn from the results of the GRP survey.

Figure 3. Radar images for the 15 crossing points along the damaged pipe (left) and the MSE analysis (right). Note that the damaged section of the pipe occurs at point 8

THE MASKING OF IRON PIPES TO GPR SURVEYS DUE TO CORROSION

It has been observed that iron pipes are weakened by corrosion processes, and in certain soil conditions the migration of iron from the pipe into the surrounding soil can effectively mask the presence of the pipe in GPR surveys (Pennock et al., 2010). Corrosion, an electrochemical process, is a natural phenomenon that greatly depends on the environmental conditions, such as aggressive soil, use of dissimilar metals, and stray electric current. As corrosion takes place over time, the corrosion products will typically migrate into the soil and will chemically alter the soil, changing both the physical and chemical properties of the soil. A current research project is aiming to investigate how the corrosion products from cast iron buried in clay soils can materially influence the soil-pipe interaction behaviour and the ability of GPR to locate the corroding pipe. Furthermore, the associated influence on the mechanism of failure of the pipe will be investigated, focusing on the geotechnical aspects of the iron-contaminated clay.
This project, which is still in the design/proto-type phase, will be a laboratory-based investigation using two experimental approaches. The first consists of consolidated clay samples between two iron plates. The iron is corroded at an accelerated rate by the application of a potential difference across the samples. The soil samples are then investigated to determine physical and chemical changes induced within the soil, using various techniques including simple geotechnical parametric tests and analytical techniques such as scanning electron microscopy and x-ray diffraction. Figures 5 and 6 illustrate changes in English China Clay when exposed to the potential difference. The conductivity (measured by TDR) increases markedly near the electrodes after the application of the 5V potential difference across the clay sample for seven days (Figure 5). The increased conductivity near the anode is believed to be a result of iron migration into the sample as the cast iron corrodes and it is believed that the conductivity increases at the cathode is due to dissolution of alumina and silica, a function of the electrokinetic process when dealing with English China Clay.

![Graph](image)

**Figure 4. Comparison of soil properties for two English China Clay samples, (top) when exposed to a 5V potential difference for seven days and (bottom) a control sample**

XRD analysis illustrates that the increase in conductivity within the clay samples is due to the migration of iron from the iron plate into the soil sample (Figure 6). Speciation modelling is being considered to see if this can explain how the iron is moving from the plate to the soil.
Figure 5. XRD analysis of (left) English China Clay in contact with the cathode and (right) English China Clay that had not been exposed to a potential difference or the iron plates

A second experimental approach is being developed that involves the introduction of different concentrations of various iron solutions into clay samples; following sample creation GPR will be used to survey the sample. It is believed that the changes in conductivity of the soil surrounding the corroding metal results in the inability of the GPR to detect the pipe (Pennock et al., 2010) and it is hoped that this experimentation will provide insight into this phenomenon.

INVESTIGATING THE RELATIONSHIP BETWEEN THE GEOTECHNICAL AND VIBRO-ACOUSTIC PROPERTIES OF A SOIL

The MTU project has focused upon furthering the understanding between the geotechnical and geophysical properties associated with electromagnetic wave propagation, as described above, for various soils. However, as vibro-acoustics is a geophysical locating technology deployed on the MTU multi-sensor platform, a complementary research project has been launched that aims to investigate the relationship between the geotechnical properties and the propagation of compression and shear waves for various soils.

An experimental approach is being developed using a triaxial apparatus, offering the possibility to apply isotropic stress conditions to a soil specimen, and shear waves will be transmitted through the various soil specimens to provide an insight into the relationship between wave speed and geotechnical properties. The shear waves (S-waves) are generated and received by bender element sensors located at opposite ends of the soil specimen and the shear wave velocity is calculated from the tip to tip distance between the two transducers (Leong et al., 2005; Oh et al., 2008).

In a traditional arrangement for the triaxial apparatus with bender elements set up as
shown in Figure 7 (left), a signal is generated by a personal computer, it is amplified by an amplifier, and a voltage pulse is applied to the transmitter, causing it to produce a shear wave. When the shear wave reaches the other end of the soil specimen, distortion of the receiver produces another voltage pulse. The receiver is directly connected to an analyser to compare the difference in time between the transmitter and the receiver as depicted in Figure 7 (right). For this research programme, the initial test arrangement uses a laptop computer to run a signal processor, which is connected to the bender elements and both sends and receives the voltage pulses, and records the time delay. By subtracting the time delay due to the system, as measured in the calibration tests, the shear wave velocity in the soil specimen can be calculated.

Figure 7. The set-up of bender elements in Triaxial apparatus (left) and associated electronics (right) (after Piriyakul, 2010)

The routine procedure of a drained consolidation sequence in a triaxial cell followed by undrained shearing is to be followed except that additional measurements of S-wave velocity are to be taken for each stage of the test. The S-wave velocity measurements are to be carried out by installing a bender element in the base pedestal and the top cap of a triaxial cell, respectively. Before and after each stage of undrained triaxial compression, S-wave velocity will be measured. Wave velocity is to be measured initially when the specimen is placed in the triaxial chamber and when the saturation stage is complete. The cell pressure in the triaxial cell is then increased and the drainage valves are opened to allow consolidation to take place. As consolidation progresses, S-wave velocities will be measured at regular intervals. Once primary consolidation is complete, i.e. the sample has undergone full compression under the cell pressure increment, a further reading of S-wave velocity will be taken. The procedure will then be repeated using further increments of cell pressure until the final target cell pressure is reached. After the final S-wave measurement has been made the specimen is to be sheared undrained and the final water content measured.
The results from the triaxial testing provide axial values of the shear stress, while shear strain can be calculated; the relationship between them is the Poisson’s ratio in undrained test conditions, and the stress-strain response of each specimen at various water contents can be plotted. In the analysis of bender element tests the time delay between the transducer and receiver signals allows the calculation of the shear wave velocity, $V_s$, and then the shear modulus, $G$, of the specimen using Equation 2, where $\rho$ is the density of the material, and the bender element test results can be analysed using transducer and receiver signals against time delay.

$$G = \rho V_s^2$$  \hspace{1cm} (2)

As a result, $G$ is more sensitive to variation in the wave speed of a specimen than it is to variation in its density. These parameters will be explored in this research. To establish a relationship between the findings from isotropic consolidation and undrained triaxial compression and bender element test results, variation of shear wave velocity during isotropic consolidation and compression (and maybe also with axial strain during undrained triaxial shearing), and wave velocity against undrained shear strength of each sample ($Cu$) after consolidation, can be plotted. Furthermore variation of shear wave velocity versus density and water content, and finally shear modulus against water content, can be plotted, thus providing insight into the relationship between wave propagation speed and the geophysical properties of a soil. As wave speed can be a factor when considering the detection and accurate (especially depth) location of a buried utility using vibro-acoustics (Royal et al., submitted), this research could contribute to the optimisation of the deployment of the multi-sensor platform.

**SUMMARY**

The impact of the ground on pipelines, and on the ability to detect buried utilities using non-invasive geophysical location techniques, can be significant. Research being undertaken at the University of Birmingham aims to further the understanding of how certain ground conditions impact upon various types of buried utility services, both from a structural view point and in terms of the ability to detect the utilities using geophysical techniques. The research into the development of understanding on how the geotechnical properties of the soils under consideration can be linked to geophysical properties (for geophysical location technologies using electromagnetic radiation or physical vibrations) will be incorporated into a knowledge-based system being developed to aid utility surveyors, essentially by strengthening the models used to predict the geophysical properties of a soil when geotechnical properties are known. The use of geophysical techniques to monitor the condition of the buried utilities
would prove a useful tool to utility network managers. It would allow for the identification of sections of a network that will require refurbishment in time, allowing a programme of maintenance and repair to be created that targets problematic areas and reduces the likelihood of catastrophic failure of the utility. Whilst the research undertaken to investigate the ability to use remote (i.e. surface-mounted) geophysical location techniques to monitor condition is still very much in the initial phase, and a great deal more research is required, the outcomes are encouraging.

REFERENCES


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